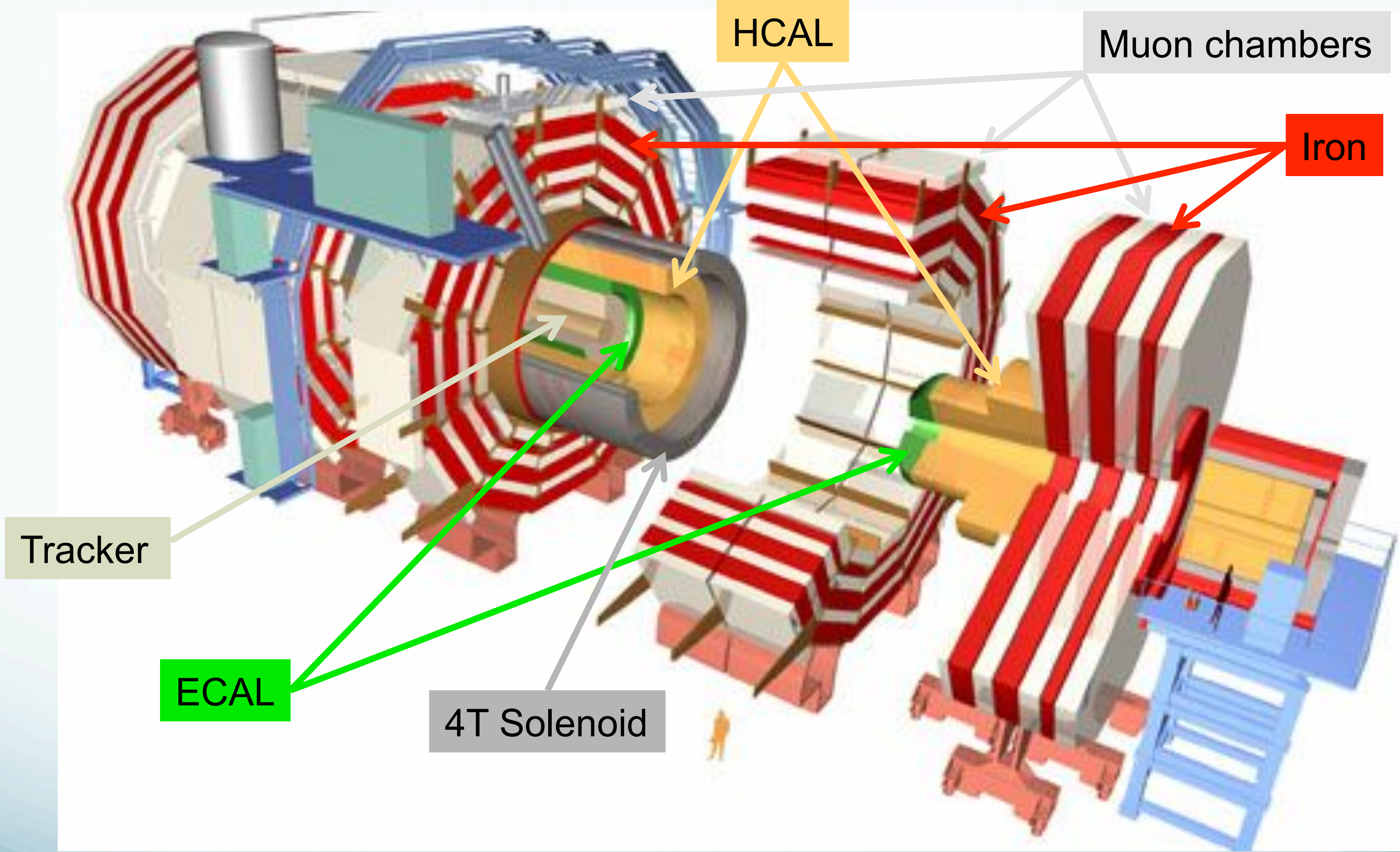
The CMS Tracker Upgrade for HL-LHC

Overview

Outline

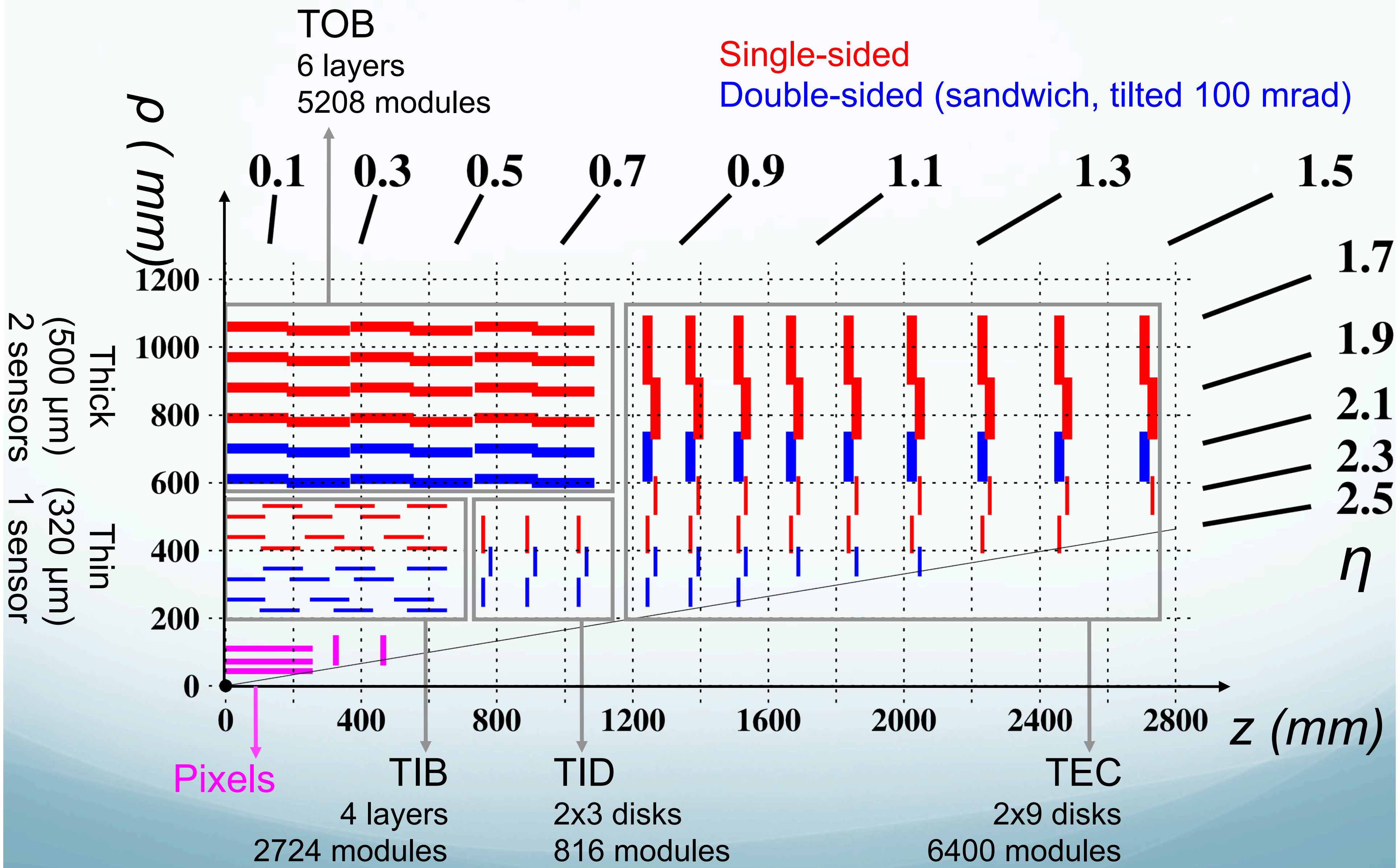
- The HL-LHC Tracker: requirements
- Overview of R&D
  - Development of "p_T modules"
  - Mechanical structures
  - Track trigger
- Expected performance
- Ultimate pixel upgrade
- Summary and outlook

The Tracker in CMS

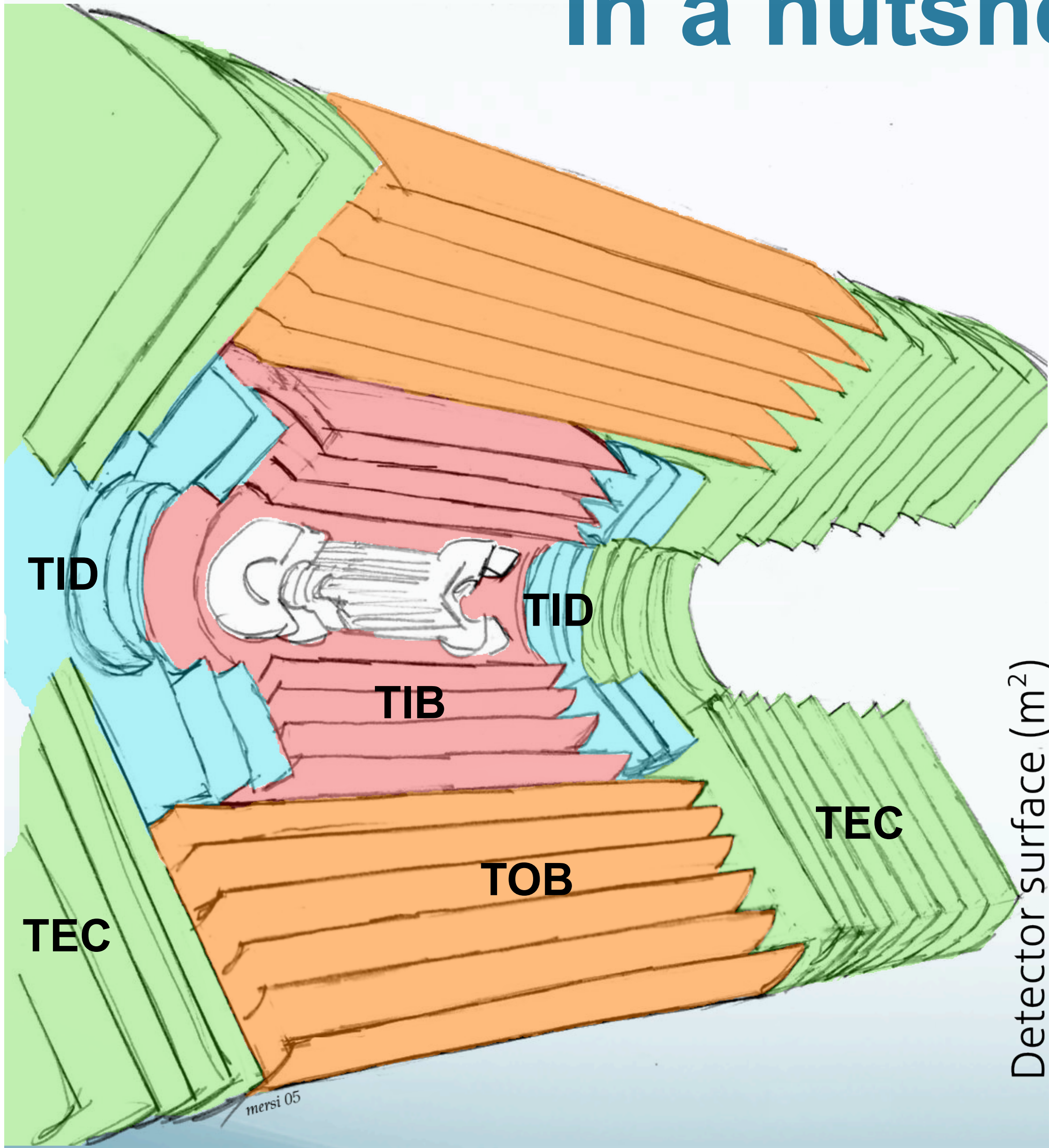


- Total weight: 12,500 t
- Overall diameter: 15 m
- Overall lenght: 21.6 m
- Magnetic field: 3.8 T

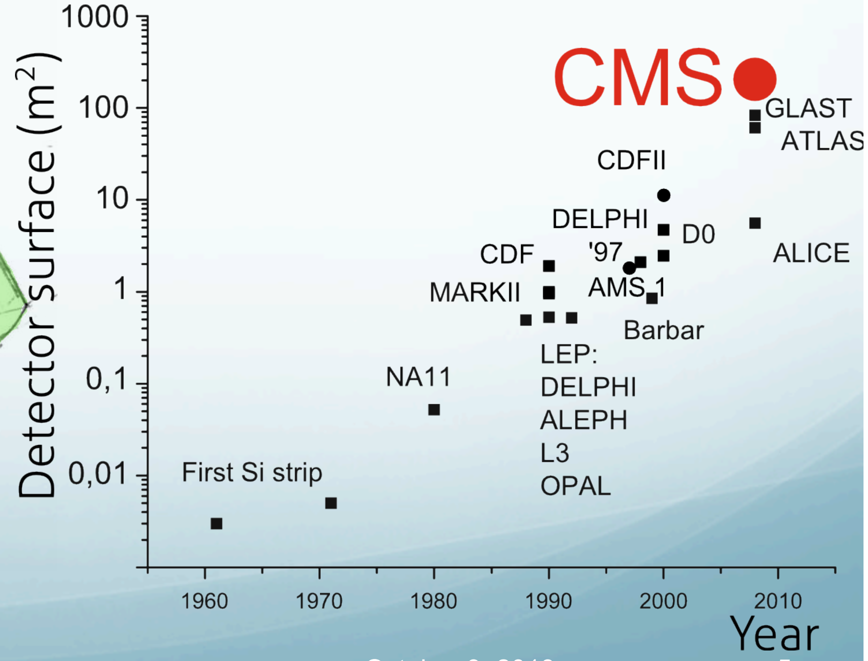
The Tracker layout



In a nutshell…

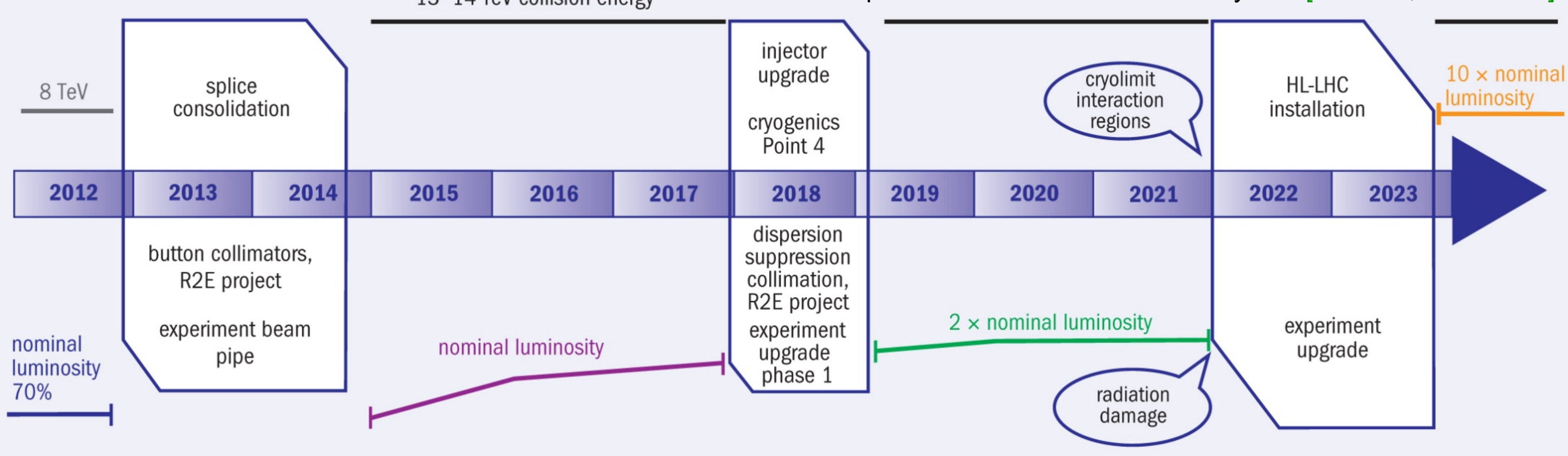


Volume	23 m^3
Active area	210 m^2
Modules	15'148
Front-end chips	72'784
Read-out channels	9'316'352
Bonds	24'000'000
Optical channels	36'392
Raw data rate:	1 Tbyte/s
Power dissipation:	30 kW
Operating T:	−10°C



The HL-LHC

A plan for the LHC in the next 10 years [L. Rossi, IPAC 2011]



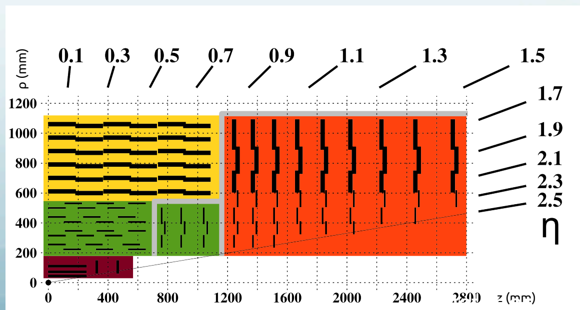
Pixel Upgrade "phase 1"

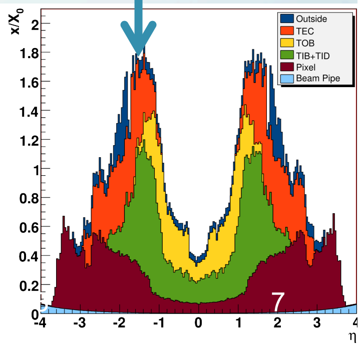
Ful Tracker Upgrade "phase 2"

Basic requirements and guidelines - I

- **Radiation hardness**
  - Ultimate integrated luminosity considered ~ 3000 fb^{-1}
    - ★ To be compared with original ~ 500 fb^{-1}
- **Granularity**
  - Resolve ~140 (and up to 200) collisions per bunch crossing, with ~ % occupancy
    - ❖ The original design figure for the present Tracker was 25!
    - ★ Requires much shorter strips!
- **Improve tracking performance**
  - Improve performance @ low p_T
  - Reduce rates of nuclear interactions, γ conversions, bremsstrahlung…
    - ★ Reduce material in the tracking volume
  - Improve performance @ high p_T
    - ★ Reduce average pitch

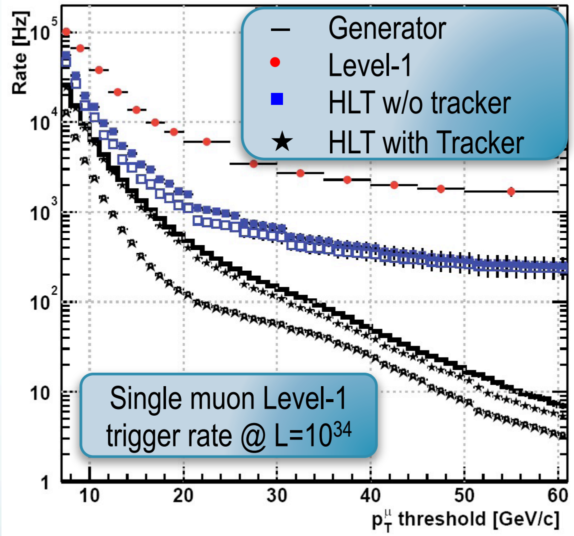
Substantially higher channel count!





Basic requirements and guidelines – II

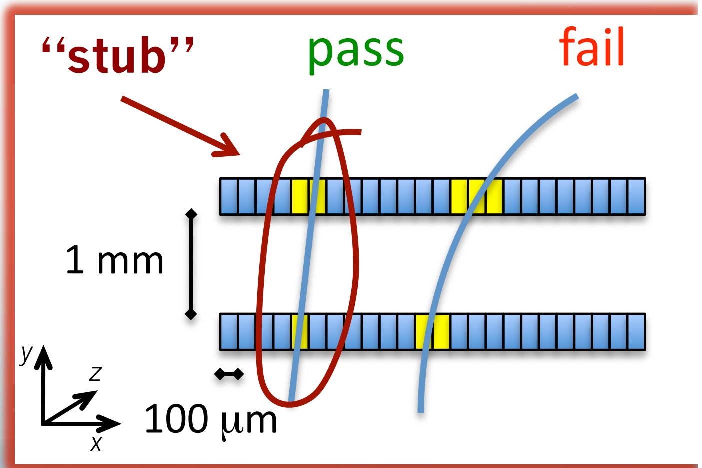
- Tracker input to Level-1 trigger
  - μ, e and jet rates would substantially increase at high luminosity
    - Even considering “phase-1” trigger upgrades
  - Increasing thresholds would affect physics performance
    - Performance of algorithms degrades with increasing pile-up
      - Muons: increased background rates from accidental coincidences
      - Electrons/photons: reduced QCD rejection at fixed efficiency from isolation
  - Even HLT without tracking seems marginal
  - Add tracking information at Level-1
    - Move part of HLT reconstruction into Level-1!



- Goal for “track trigger”:
  - Reconstruct tracks above 2 GeV
  - Identify the origin along the beam axis with ~ 1 mm precision

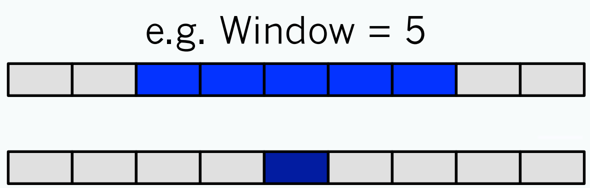
General concept

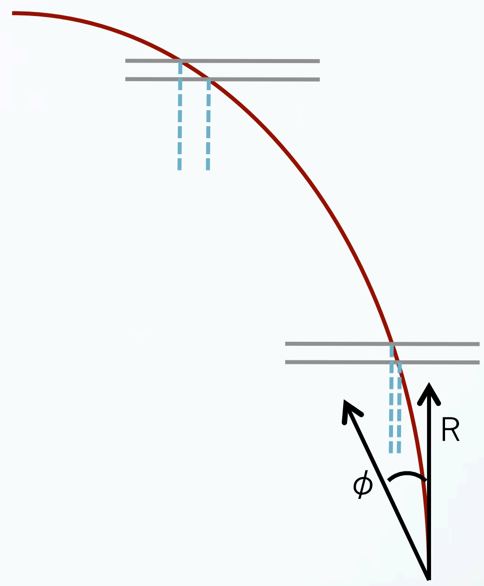
- Silicon modules provide at the same time "Level-1 data" (@ 40 MHZ), and "readout data" (upon Level-1 trigger)
  - The whole tracker sends out data at each BX: "push path"
- Level-1 data require local rejection of low-p_T tracks
  - To reduce the data volume, and simplify track finding @ Level-1
  - Threshold of ~ 2 GeV $\Rightarrow$ data reduction of one order of magnitude or more
- Design modules with p_T discrimination ("p_T modules")
  - Correlate signals in two closely-spaced sensors
  - Exploit the strong magnetic field of CMS
- Level-1 "stubs" are processed in the back-end
  - Form Level-1 tracks, p_T above ~2 GeV
  - To be used to improve different trigger channels



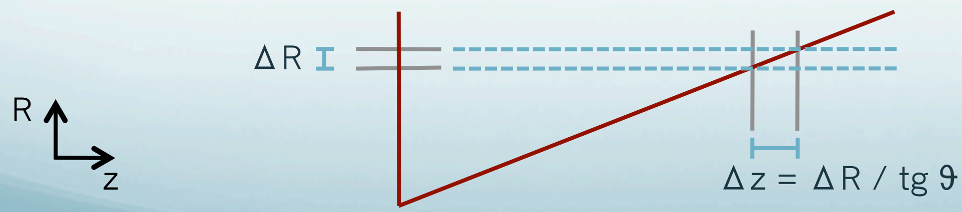
More on p_T modules working principle

- Sensitivity to p_T from measurement of $\Delta(R\varphi)$ over a given ΔR
- For a given p_T, $\Delta(R\varphi)$ increases with R
  - A same geometrical cut, corresponds to harder p_T cuts at large radii
  - At low radii, rejection power limited by pitch
  - Optimize selection window and/or sensors spacing
    - ★ To obtain, ideally, consistent p_T selection through the tracking volume



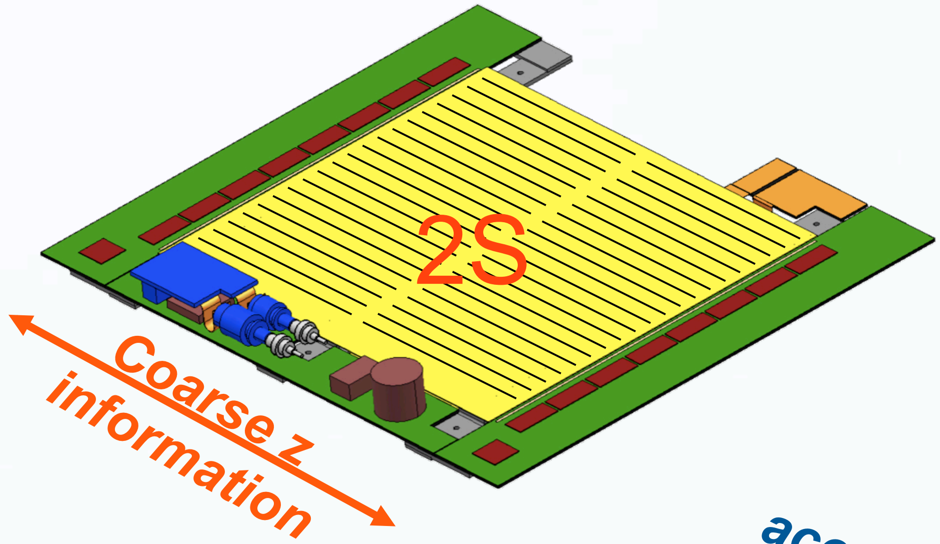


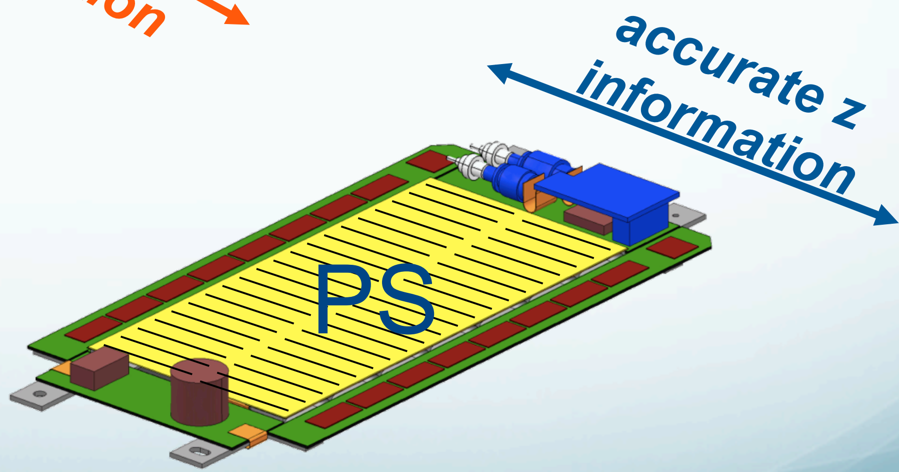
- In the barrel, ΔR is given directly by the sensors spacing
- In the end-cap, it depends on the location of the detector
  - End-cap configuration typically requires wider spacing



p_T modules

2 Strip sensors
Strips: 5 cm × 90 µm
Strips: 5 cm × 90 µm
P = 2.7 W
~ 92 cm^2 active area
For r > 60 cm



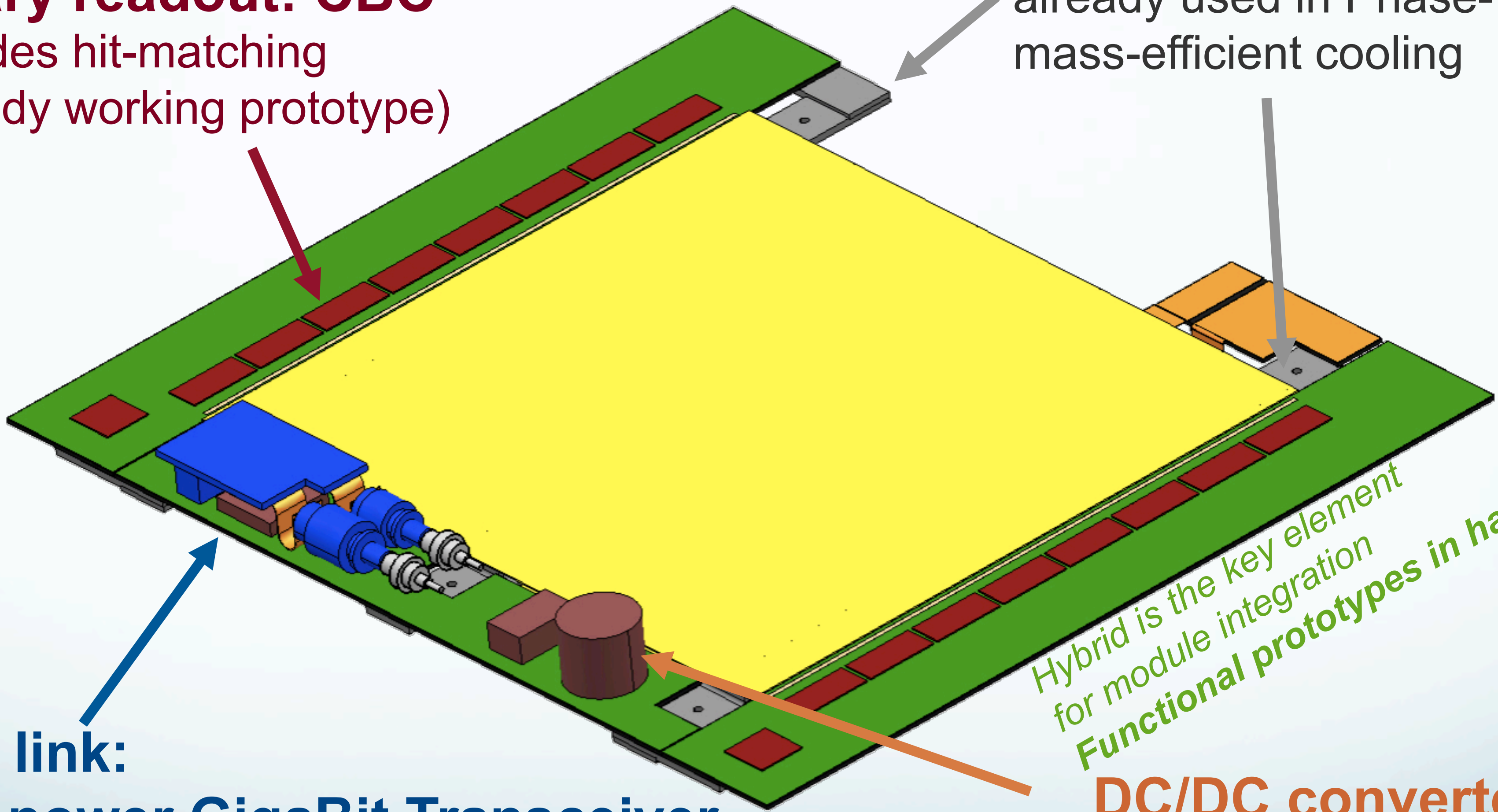


Pixel + **S**trip sensors
Strips: 2.5 cm × 100 µm
Pixels: 1.5 mm × 100 µm
P = 5.0 W
~ 44 cm^2 active area
For r > 20 cm

2S module

Binary readout: CBC
provides hit-matching
(already working prototype)

CO_2 cooling
already used in Phase-1
mass-efficient cooling



Hybrid is the key element
for module integration
Functional prototypes in hand!

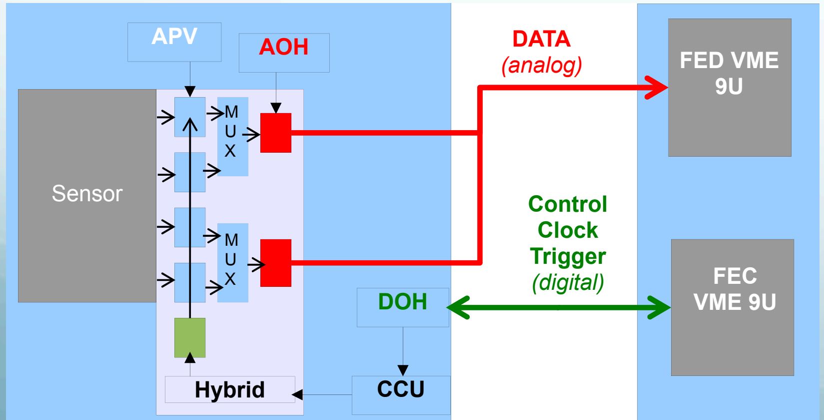
Data link:
Low-power GigaBit Transceiver
lpGBT currently under development
integrated at module level

DC/DC converter
already used in Phase-1
10 V lines: lower current, lower material

Electronics: old and new

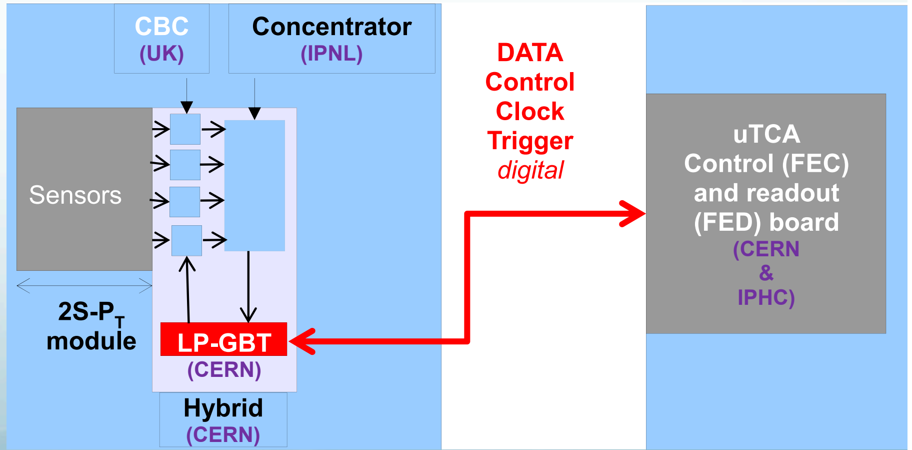
OLD

- Readout (unidirectional) and control (bidirectional) in two separate links and separate systems of front-end and back-end boards. Slow-control data in readout link.
- Analogue readout. Allows for common mode subtraction and energy loss measurement.
- 0.25 µm ASIC; > 2 mW/ch.

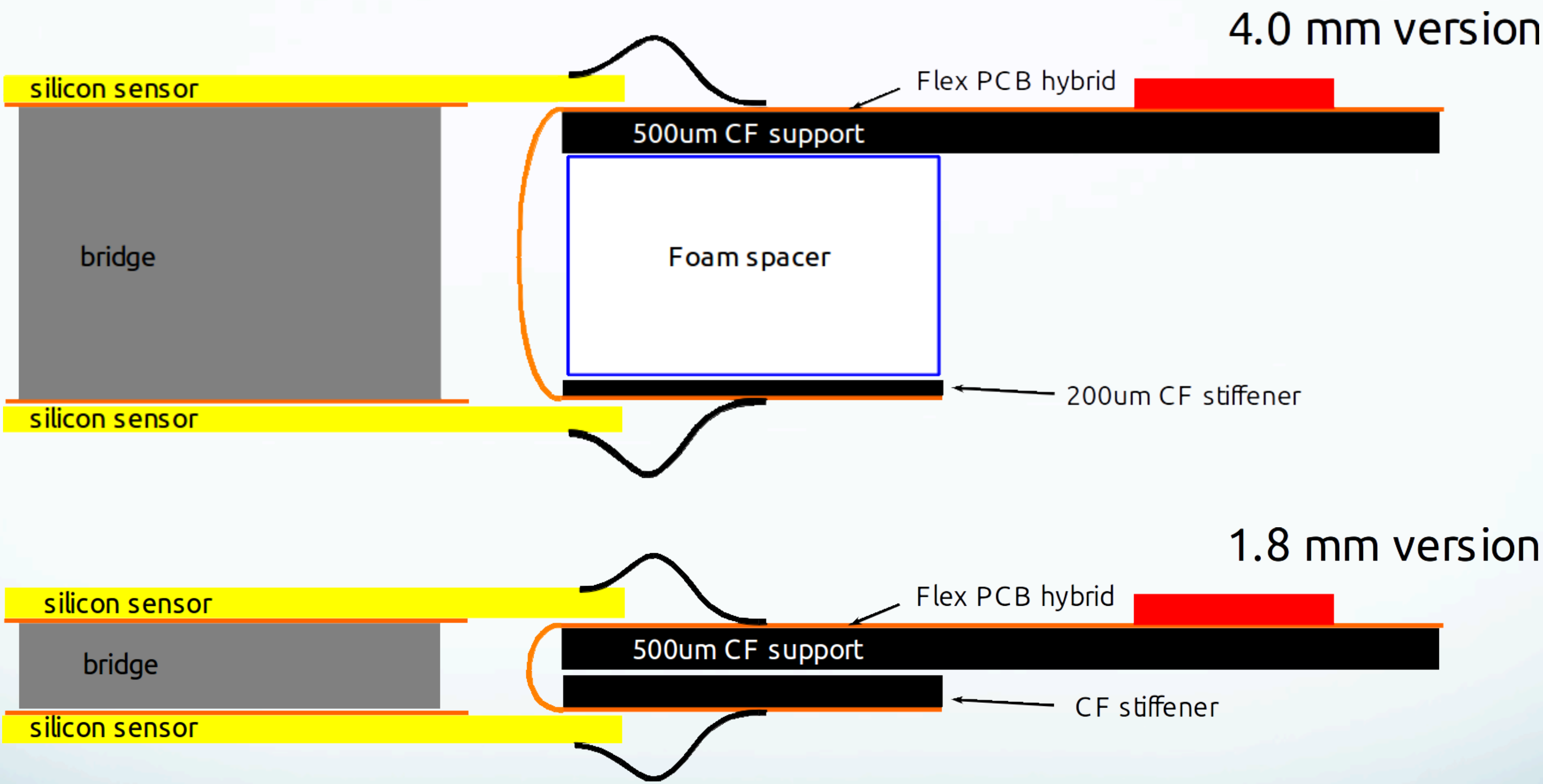


NEW

- Single bidirectional link carries all the data, including new L! trigger output!
- Binary readout. Requires perfect grounding! More suitable for high granularity and low power per channel
- 130 nm (or 65 nm) ASIC; about 0.3 mW/ch for the strips.

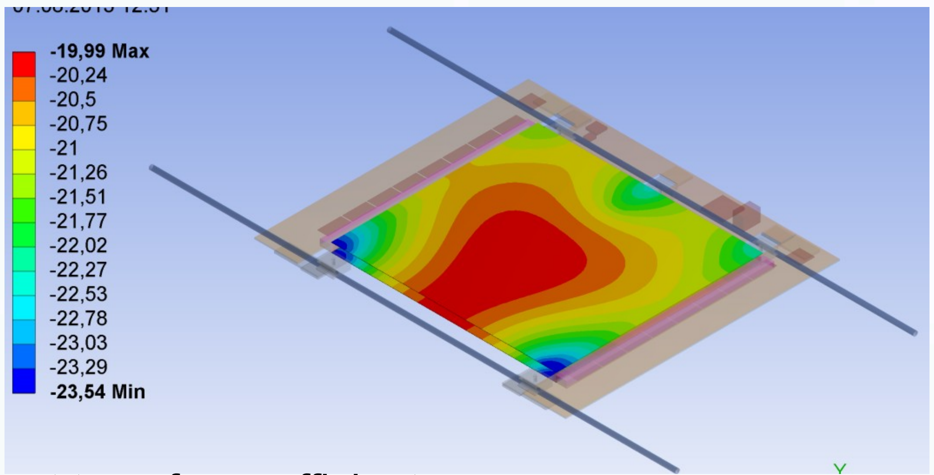


Connectivity



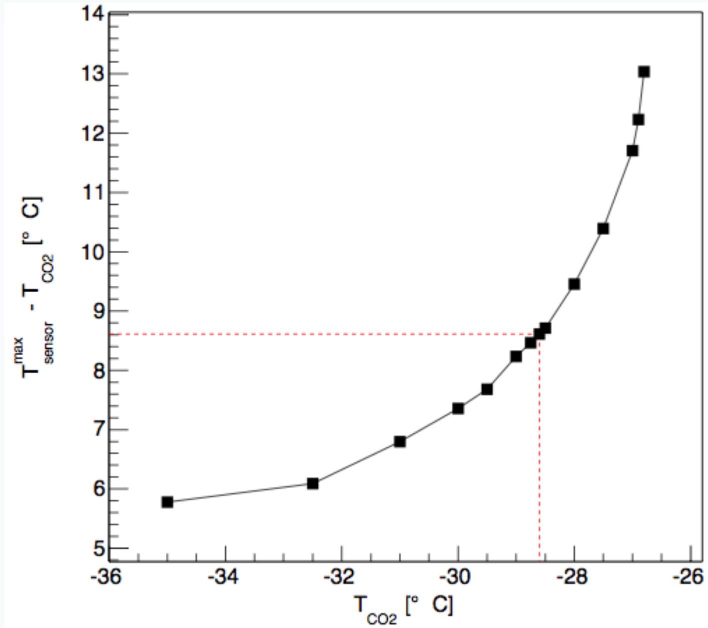
Different sensor spacings obtained by variations of the same design

2S modules: thermal performance



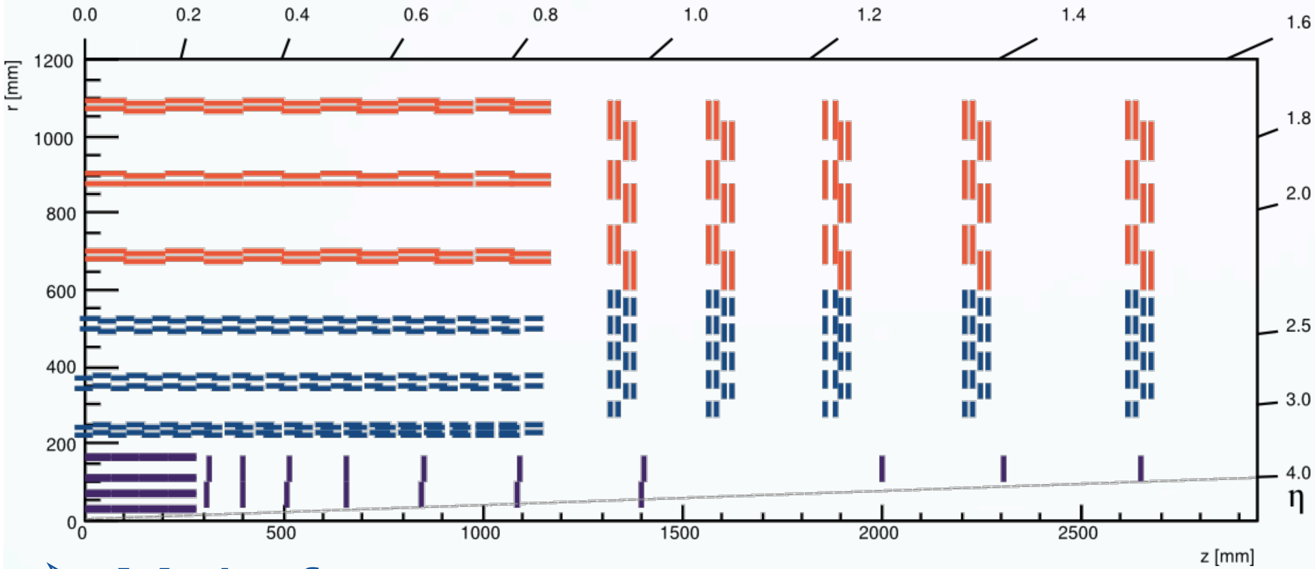
Heat transfer coefficients:

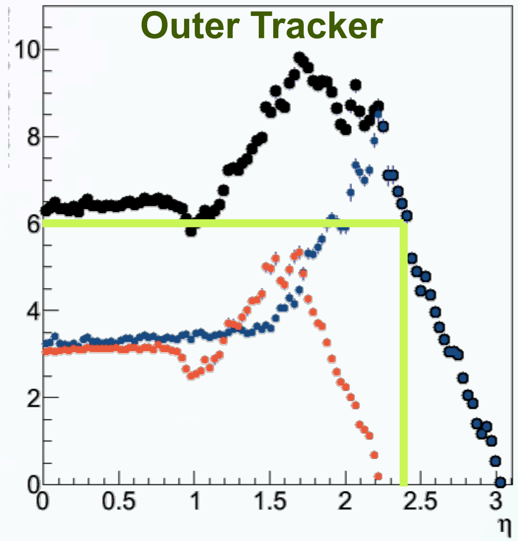
- pipe → CO2 = 5'000 W/m^2/K
- module → cooling blocks = 10'000 W/m^2/K



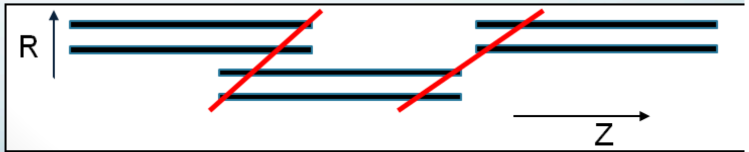
- Simulation includes the dark current model for a fluence of 7.35x10^{14} neq/cm^2 (worst possible condition)
- T_{CO2} tuned to obtain **T_{SENSOR} ≤ - 20 °C**
  - Temperature gradient on sensors = 3.5 °C
  - **T_{CO2} = -28.6 °C** to obtain T_{SENSOR} < -20 °C
  - Thermal runaway at T_{CO2} ≈ -27 °C

Tracker Layout





- Main features
  - ×4 granularity in strip sensors (avg)
  - 3 more layers of pixellated sensors in the Outer Tracker
    - ★ Unambiguous 3d coordinates – helps track finding in high pile-up
  - 12 hits up to η ≈ 2.4 available at Level-1
  - Extended coverage up to η ≈ 4
  - Form hermetic surfaces (cyliners and disks) for stub finding
    - ★ Taking into account IP spread



Tracker in Numbers

OLD	NEW

OLD

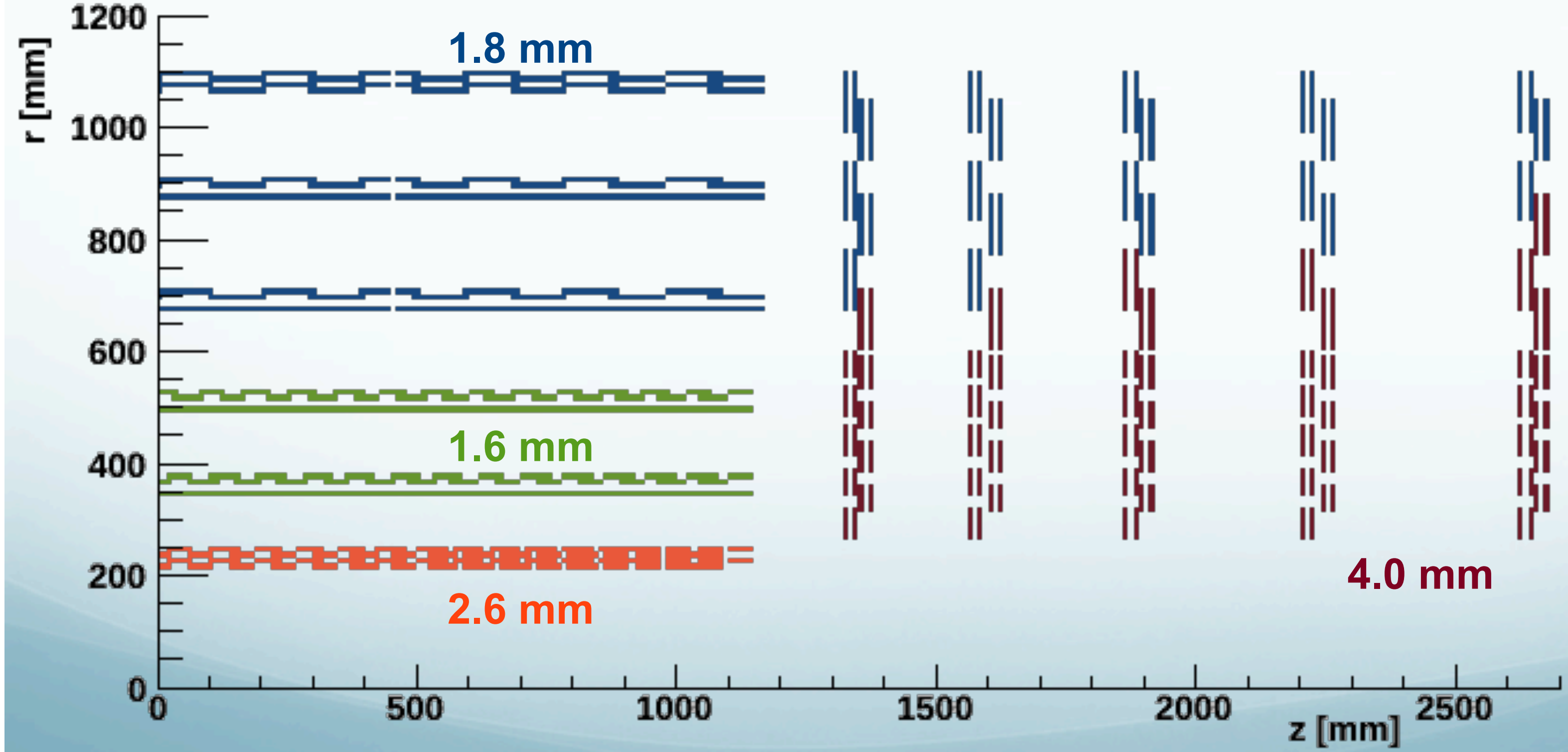
- Total n of modules 15,148
- Total active surface 210 m^2
- Total n of strips 9.3 M
- Power in the tracking volume ~ 30 kW

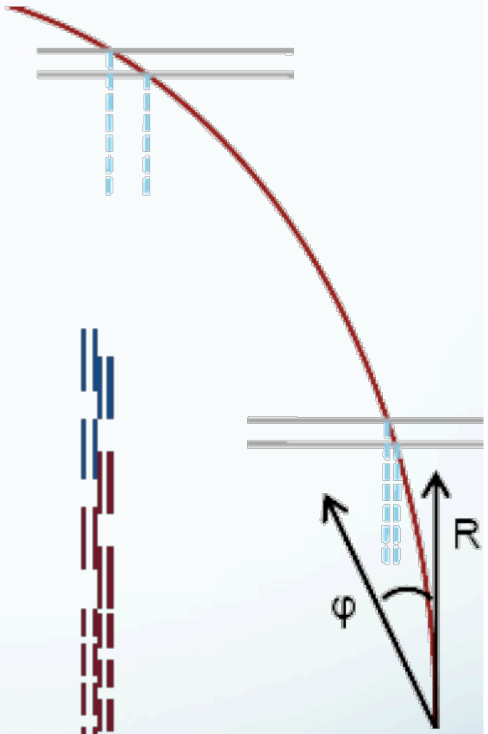
NEW

- N of modules 15,508
  - 7084 PS modules
  - 8424 2S modules
- Total active surface 218 m^2
  - 155 m^2 strips (2S)
  - 31 m^2 strips (PS)
  - 31 m^2 macro-pixels (PS)
- Total n of strips 47.8 M
- Total n of pixels 218 M
- Power in the tracking volume ~70 kW

Optimization of module parameters

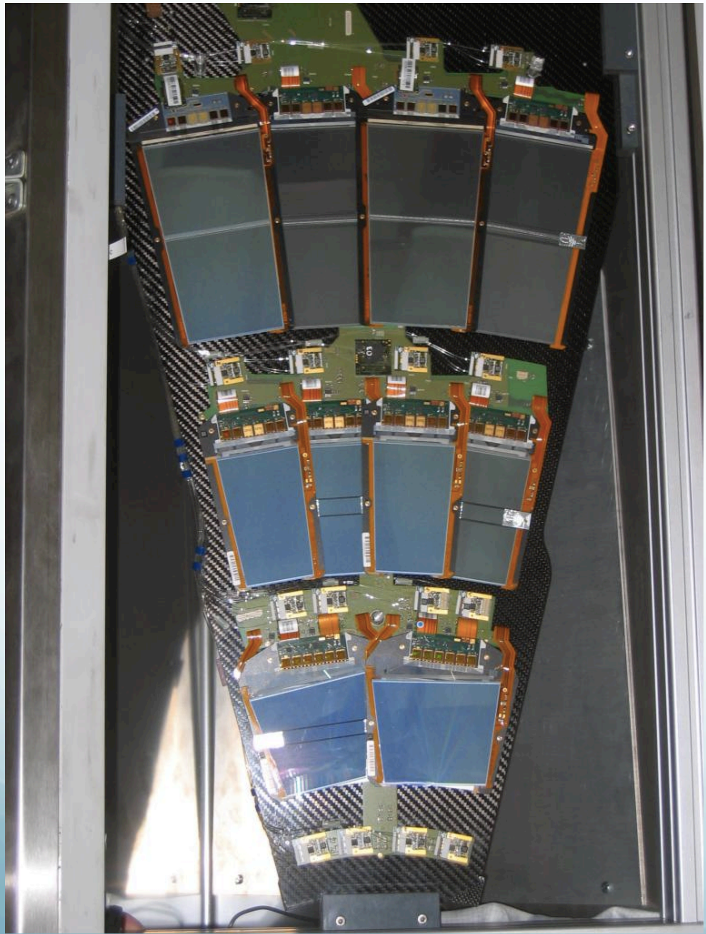
- Keep as targets:
  - <1% efficiency @ p_T = 1GeV
  - maximize efficiency @ p_T = 2 GeV
- Limit choice of spacing to “a few” different values
- Optimize width of acceptance window at the same time
  - between 3 and 16 strips for the example below

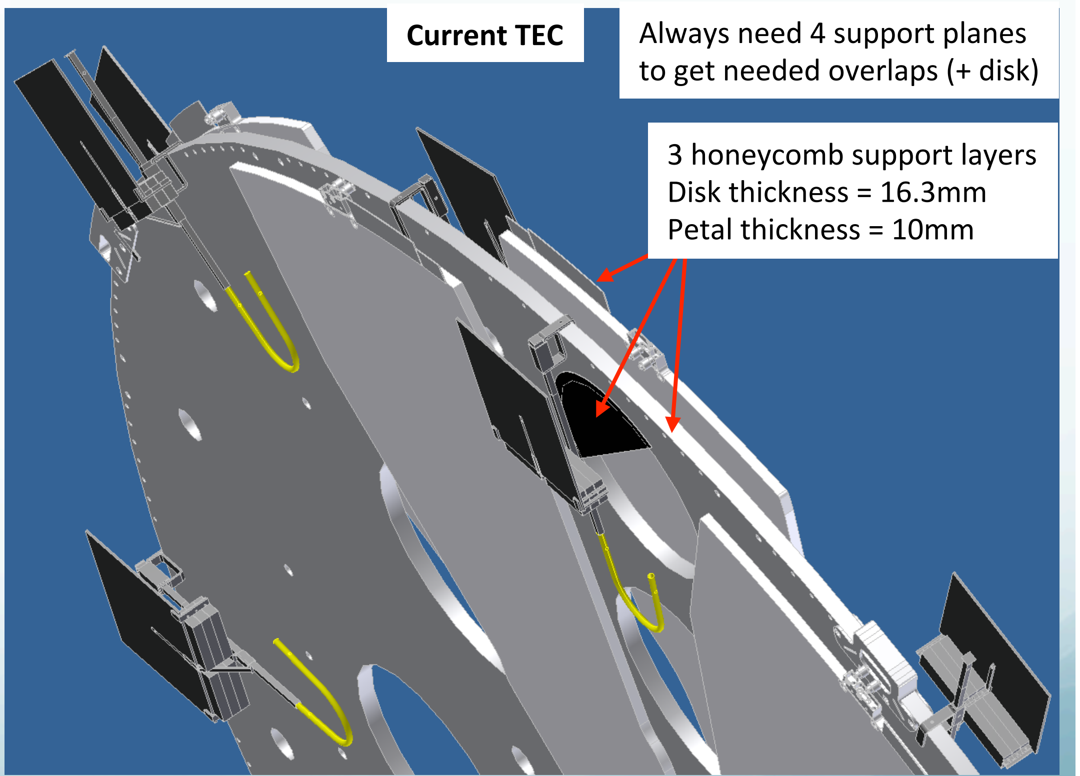




Mechanics: endcap

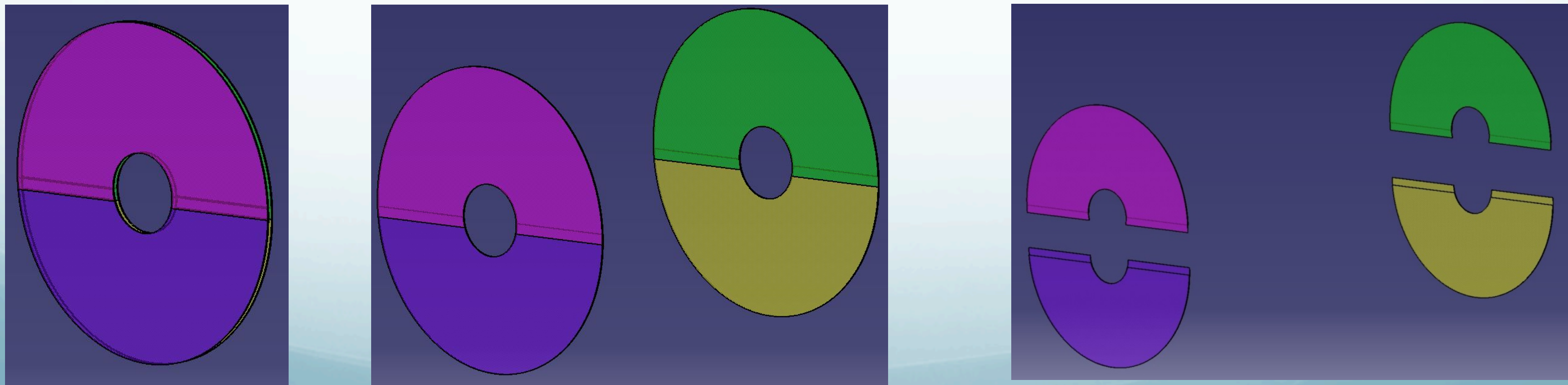
- Current TEC concept
  - "Petals" on disk
  - Petals populated with wdge-shaped modules



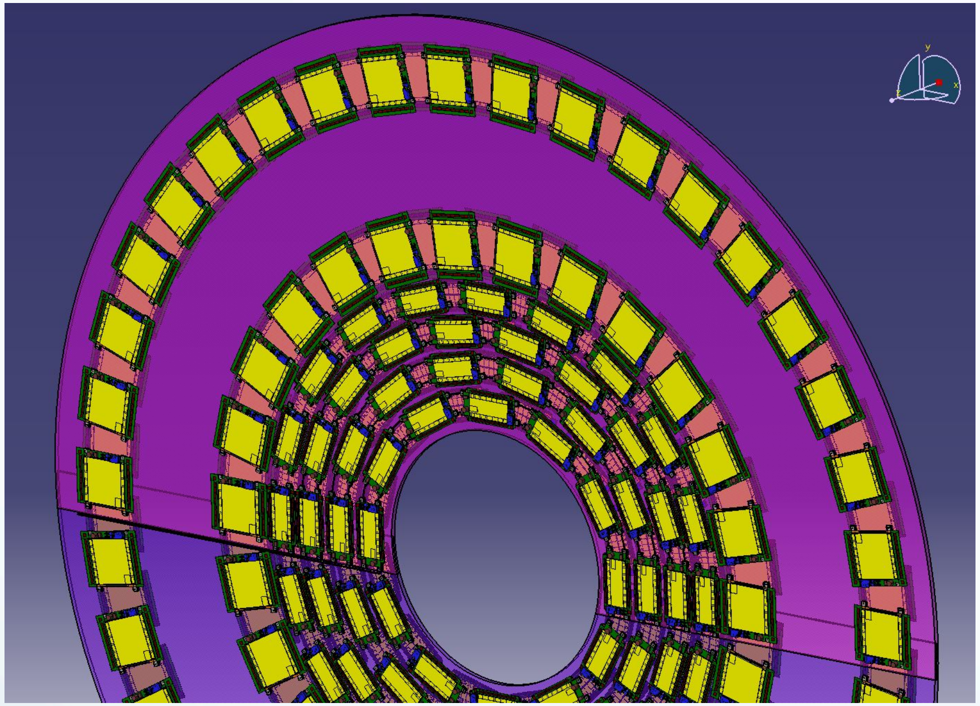


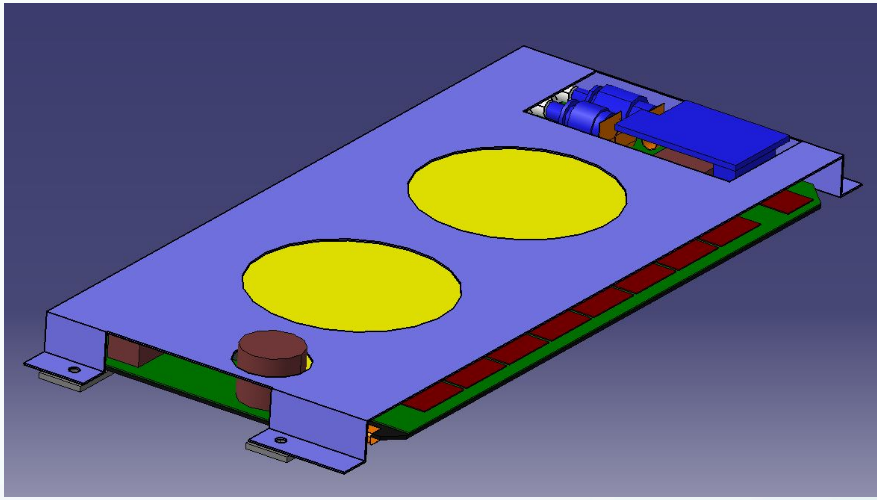
HL-TEC

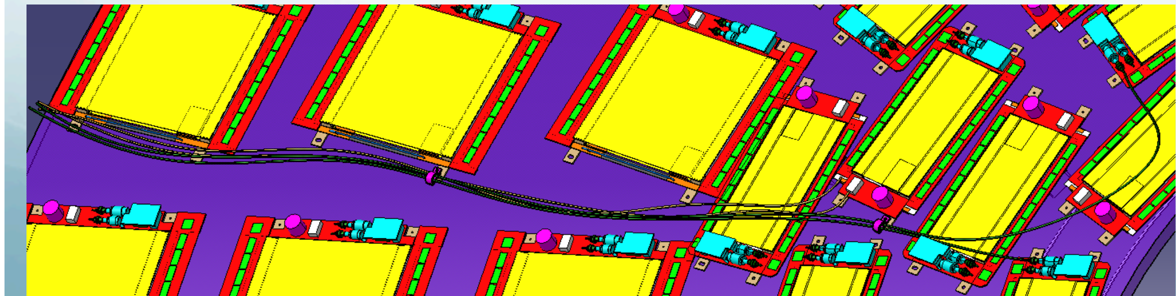
- Double-disk concept
  - Each disk split in two dees
    - ★ Eliminates the central support
  - Larger units allow to make use of same rectangular modules as in barrel
    - ★ Implies some additional overlap
    - ★ Greatly simplifies production
      - ❖ N.B. The HL-TEC disk has 15 rings wrt 7 in present TEC!
      - ❖ Pitch-adpters are not conceivable with the increased channel density



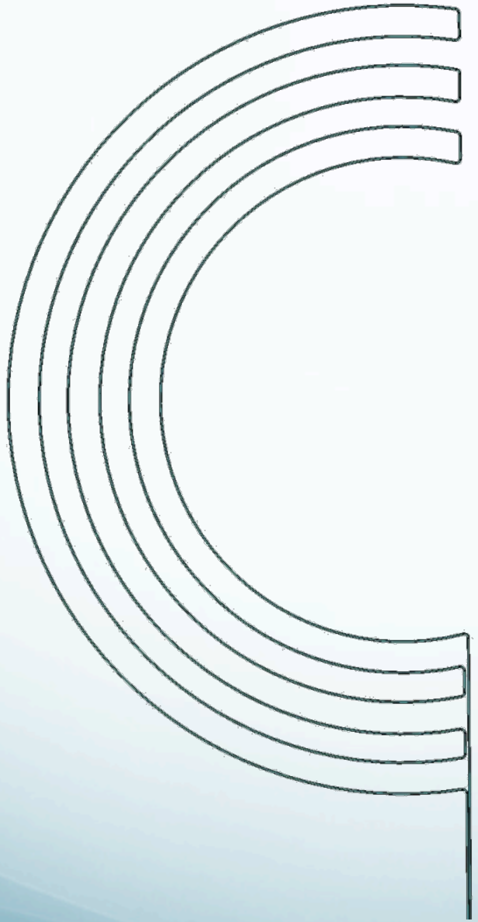
Overlaps and services

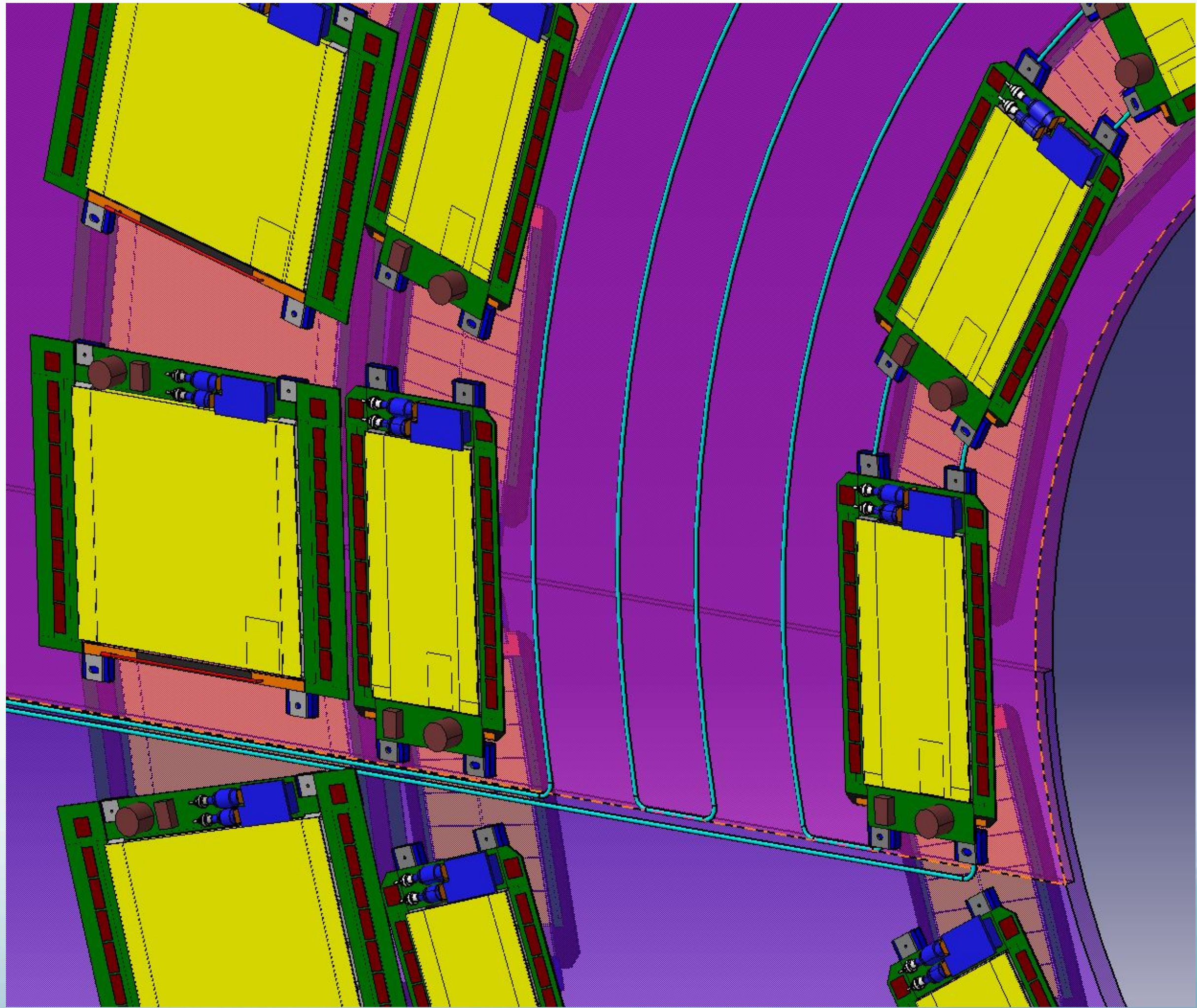




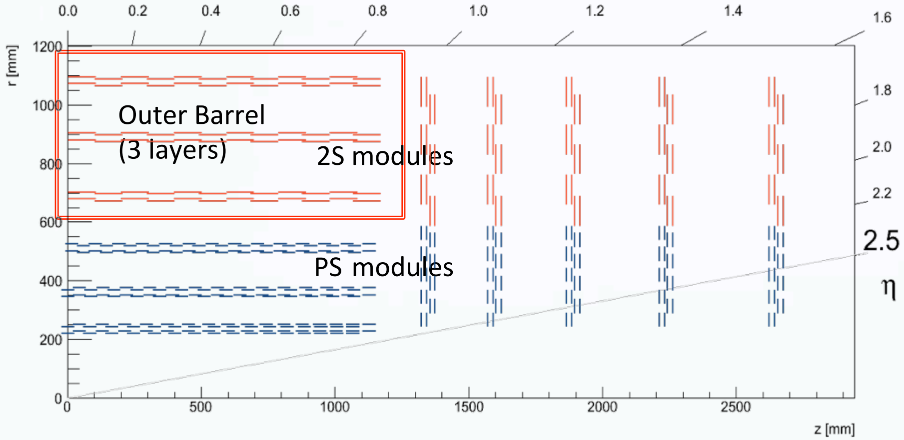


Cooling





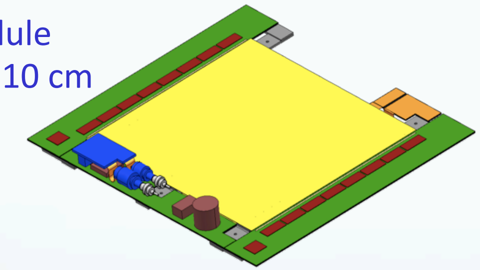
Outer Barrel concept



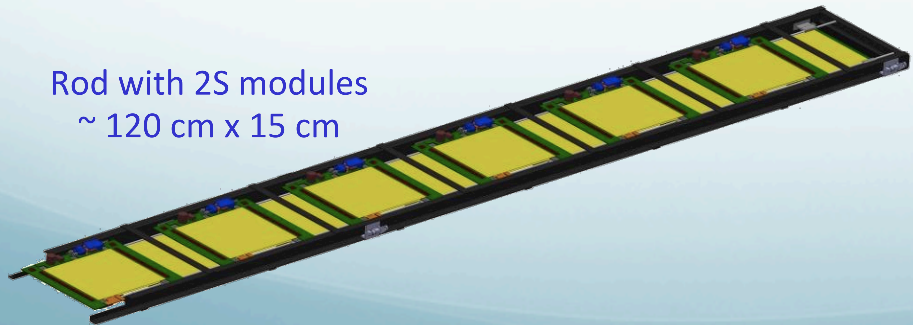
Based on the current TOB design

- 1 support wheel
- Rods installed from the two ends

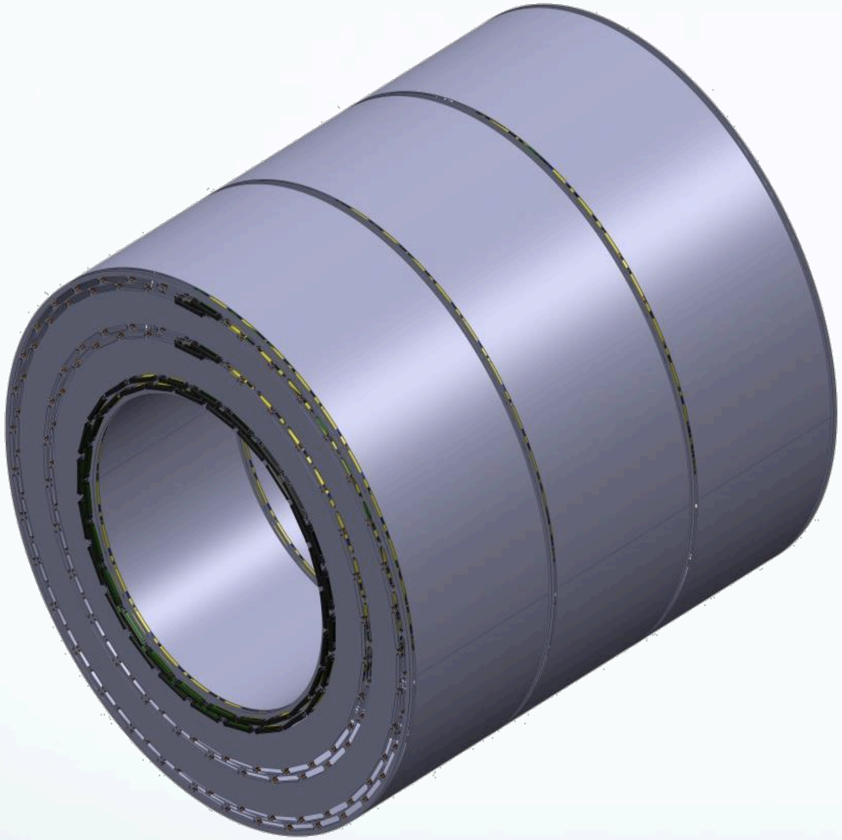
2S module
~ 10 cm x 10 cm

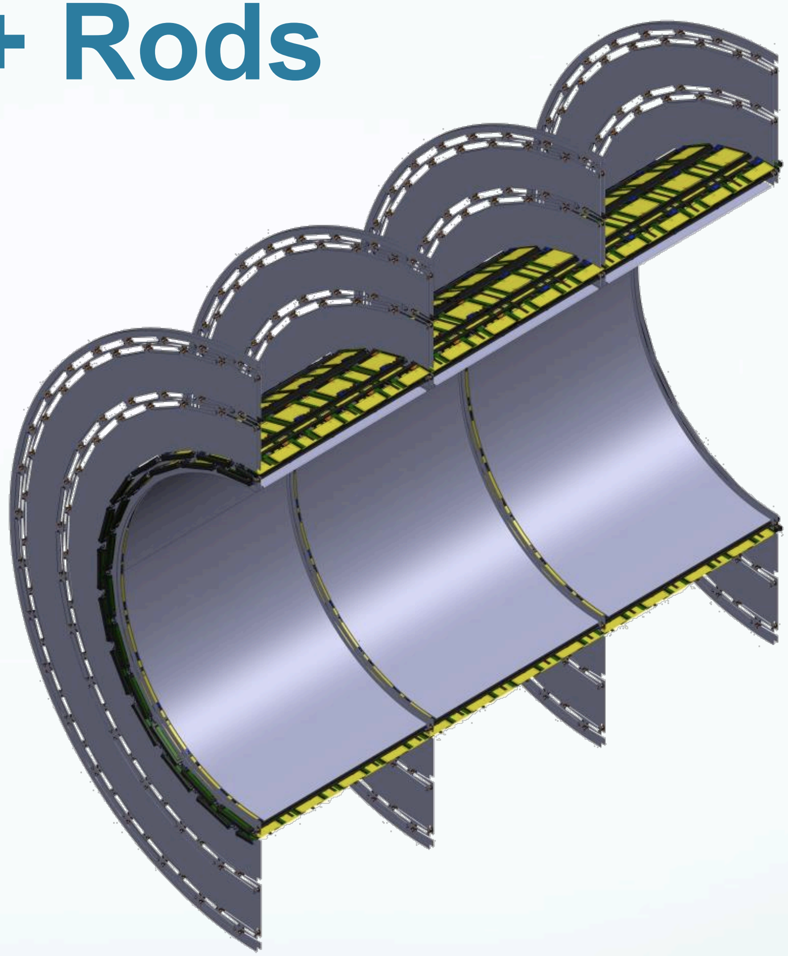


Rod with 2S modules
~ 120 cm x 15 cm



Wheel + Rods



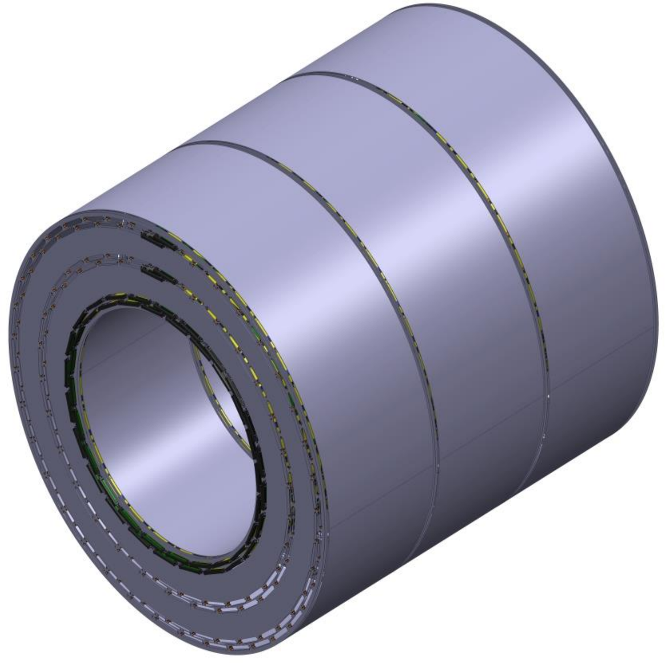


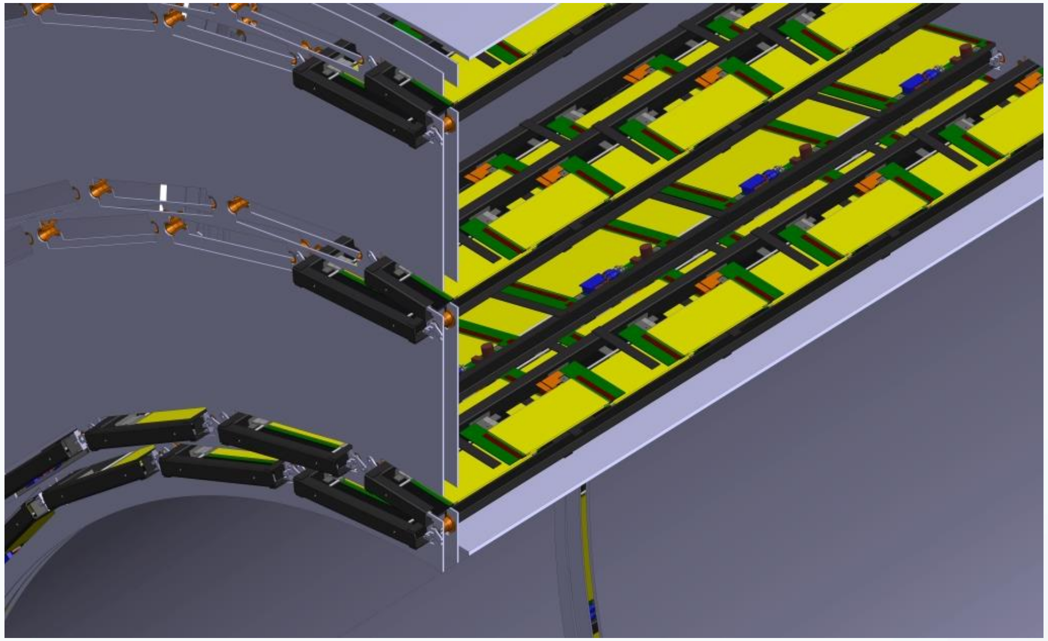
- Wheel = 4 disks joined together by 3 inner and 3 outer cylinders
- Rods are half length of the barrel, with overlap in the middle
- Rods inserted from the two ends, each rod supported by two disks

Module cooling

- In old TOB: cooling pipes on the outside of the Rod C-profiles
- Current studies: cooling pipe inside C-profile, closer to the modules
  - Tight space, but seems OK
  - Strength of structure to be re-evaluated (notably in cold)

Cooling





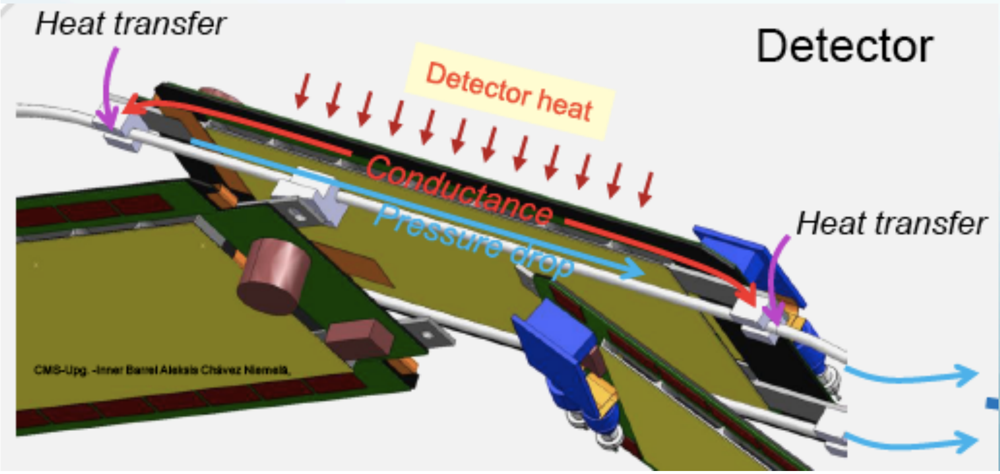
Layer	L1	L2	L3	Totals
# mod	1152	1488	1824	4464
along phi	48	62	76	
mod/rod	12	12	12	
W/mod	3.5	3.5	3.5	
W/rod	42	42	42	
W one end	2016	2604	3192	7812
W total	4032	5208	6384	15624

- Two rods in series give "CO2-suitable" cooling circuits:
  - 2 x 2.5 m = 5 m pipe length with 1.5 - 2 mm pipe diameter.
  - 84 W per line
  - 186 lines in total (93 per end)
  - 186 supply capillaries from manifolds at TK Bulkheads
  - Return pipes (size?) to manifolds at TK Bulkheads
    - ★ Alternative: return manifolding at the TOB end

Cooling: old and new

OLD

- Liquid C_6F_{14}
- Transfer heat into liquid (+ 2°C over a detector loop)
- Design goals were -10°C silicon; -20°C coolant
- Design goals not really achieved…



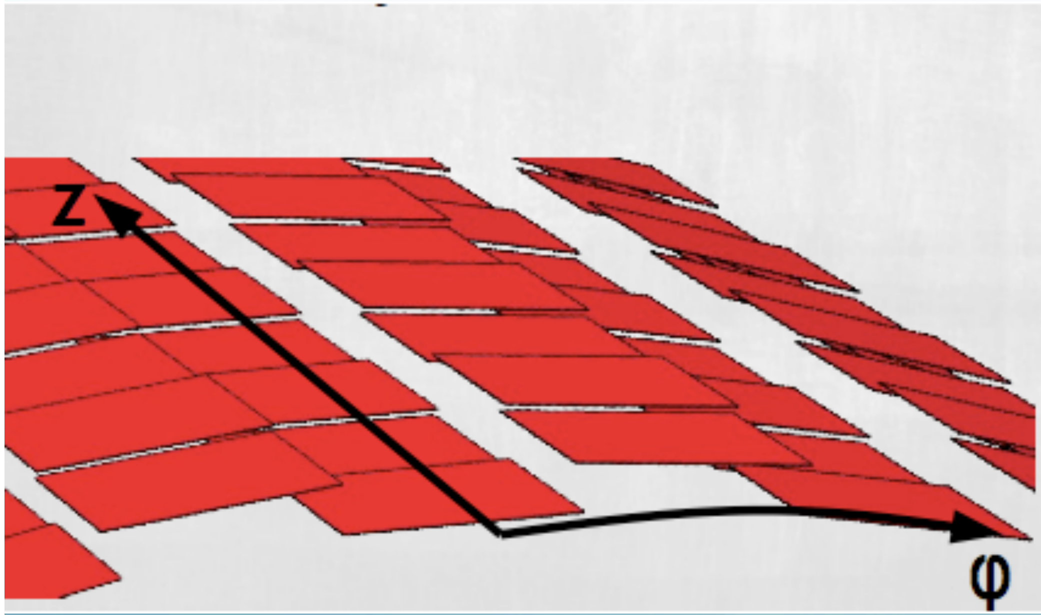
NEW

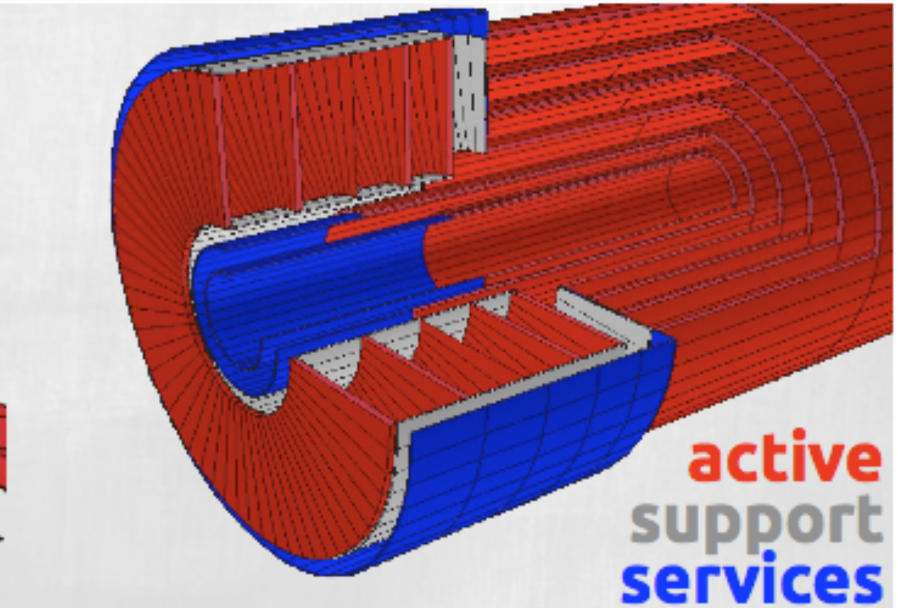
- Two-phase CO_2
- Pump in liquid CO_2; evaporate CO_2 at constant temperature along the cooling loop. Much better heat transfer coefficient!
- MUST make sure that "boiling" starts before entering the detector, and sufficient liquid remains at the end! Pressure drop along the pipes translate to decrease in temperature!
- Complicated process… a lot of thermodynamics!
- Design goals are -20°C silicon; -30°C coolant

Evaluation of different tracker geometries and options: layout modelling

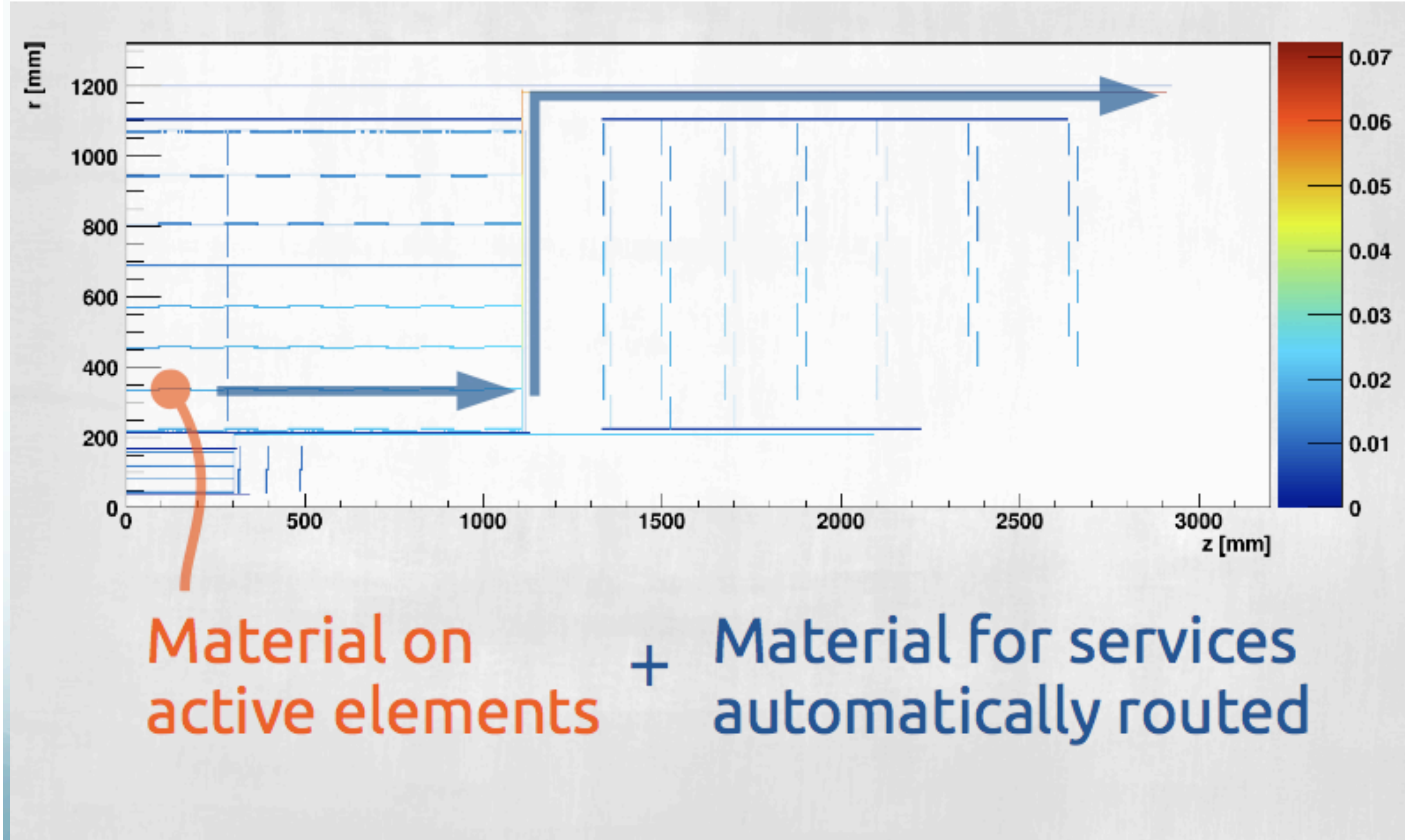
- Dedicated standalone software package©
  - © N. De Maio, S. Mersi, G. Bianchi
    - Based also on work from V. Karimaki and G. Hall

- Allows to place in space active and passive volumes
  - Starting from a small sets of simple parameters

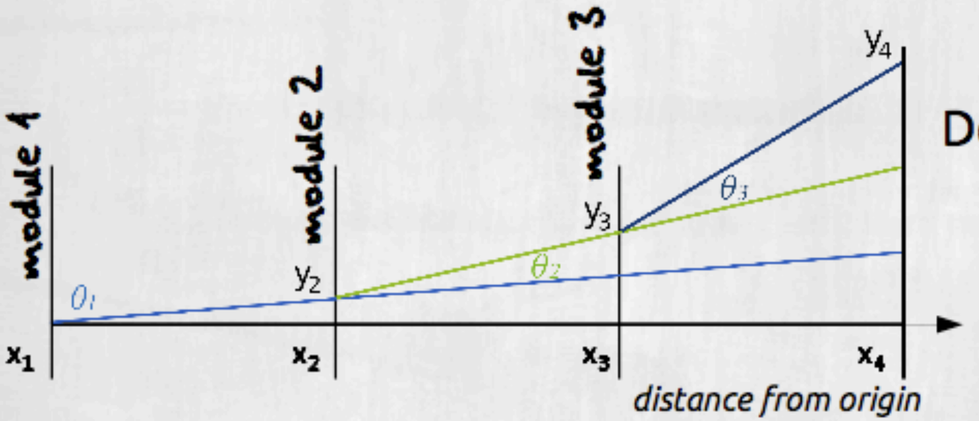




➢ Simple (semi-automatic) modelling of services



- Implements estimates of tracking performance
  - Use measurement errors to estimate the errors in track fit parameters
  - **Multiple scattering** treated as (correlated) a measurement error



Deviation due to scattering:

$$y_n = \sum_{i=1}^{n-1} (x_n - x_i)\,\theta_i$$

Error correlation matrix:

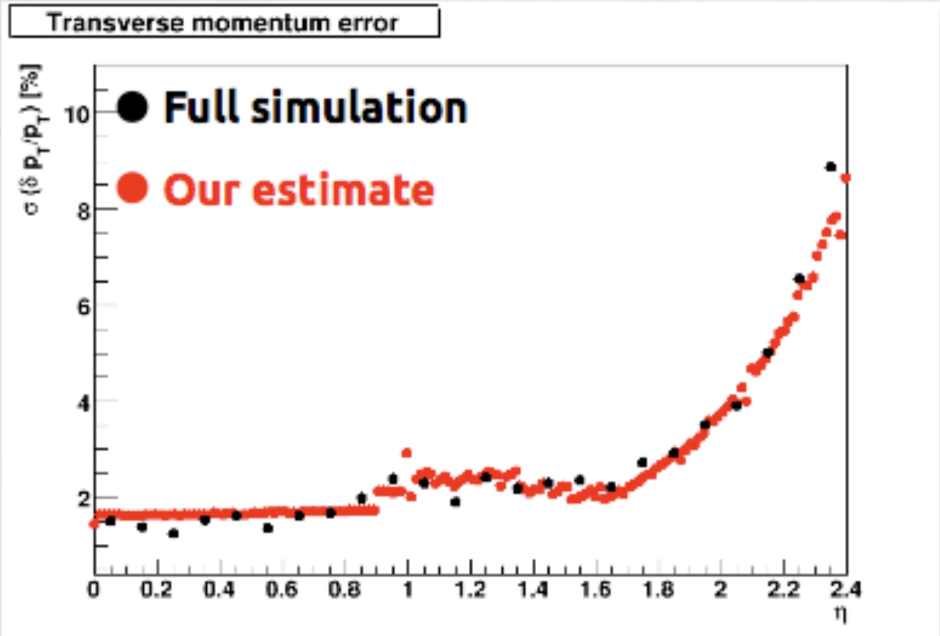
$$\sigma_{n,m} = \langle y_n y_m \rangle = \sum_{i=1}^{n-1} (x_m - x_i)(x_n - x_i)\langle \theta_i^2 \rangle$$

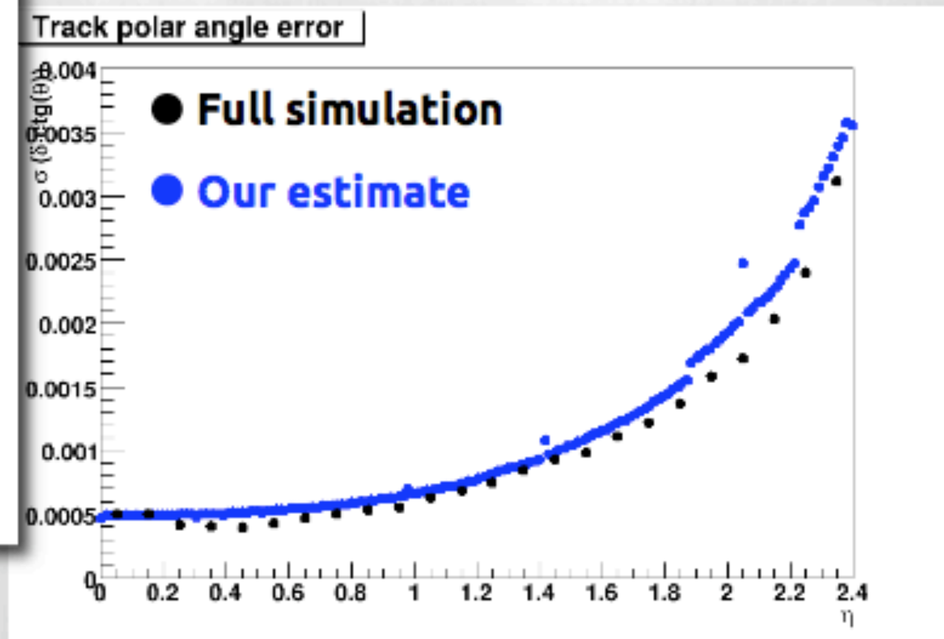
$$\sigma_n^2 = \frac{p^2}{12}$$

- As well as fraction of interacting particles
- Can be used in the same way to evaluate trigger performance potential

- Validated by modelling the present tracker

10 GeV

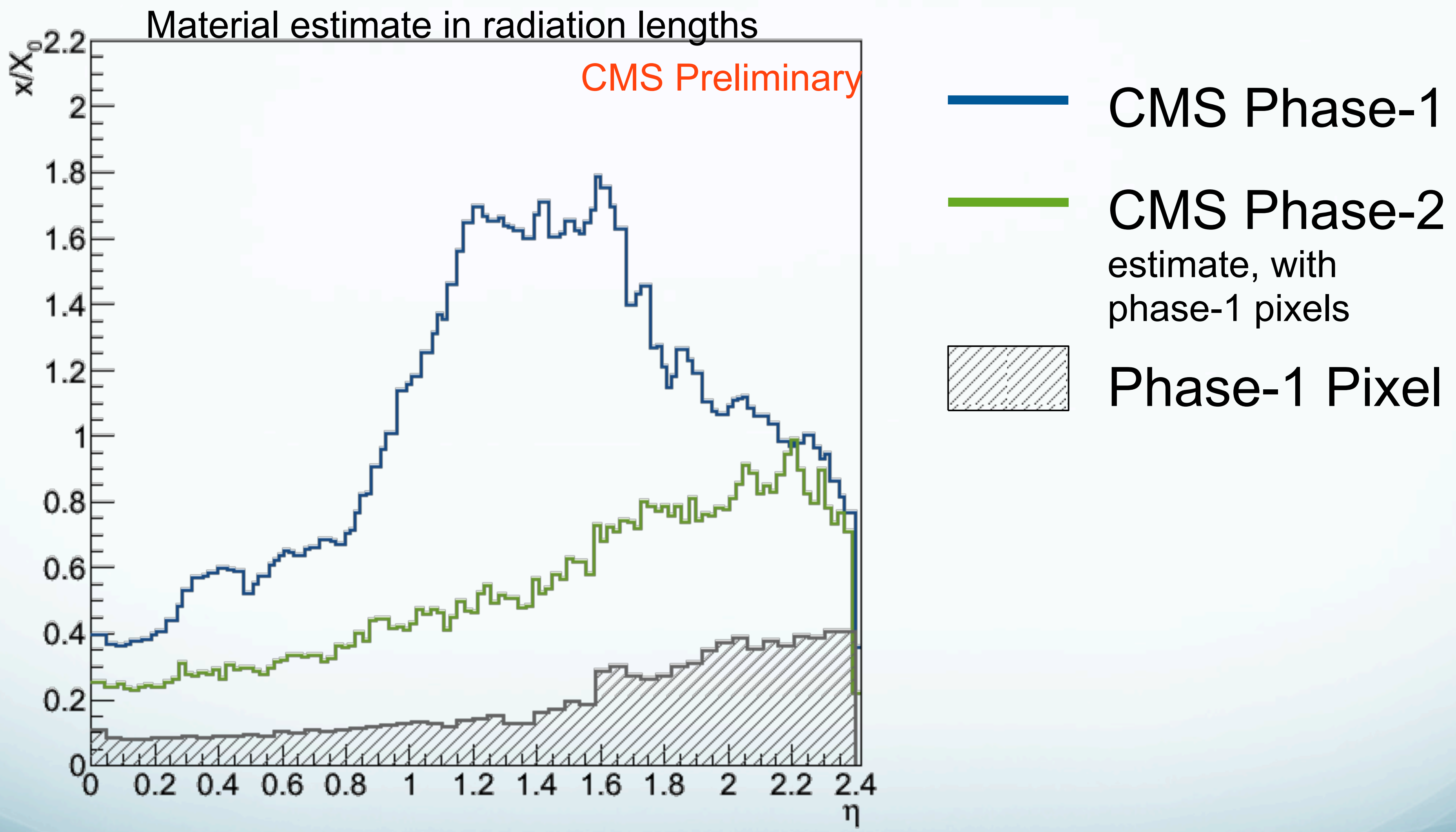




100 GeV

- Excellent accuracy out of the box!

Material



Will the "phase-2" pixel detector be as light as the phase 1?

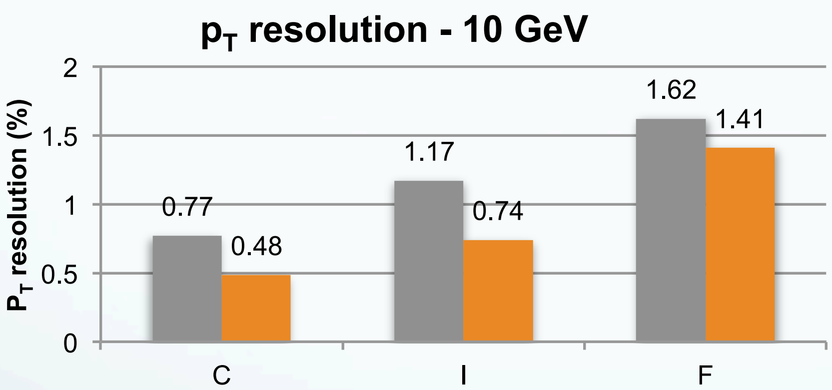
Some performance highlights

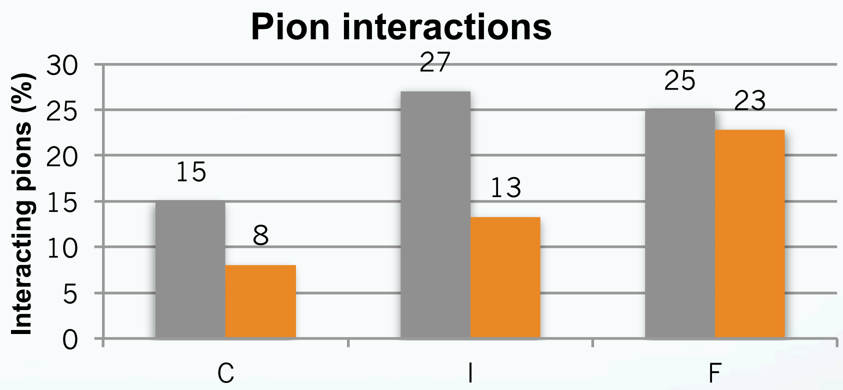
- Calculated performance with a “phase-1” pixel detector

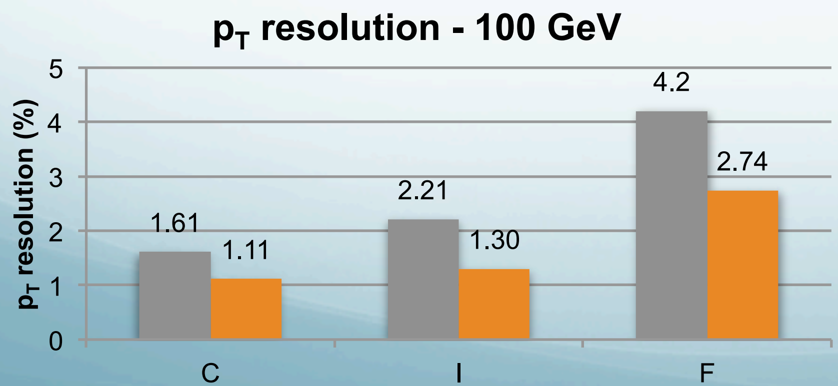
Rapidity regions

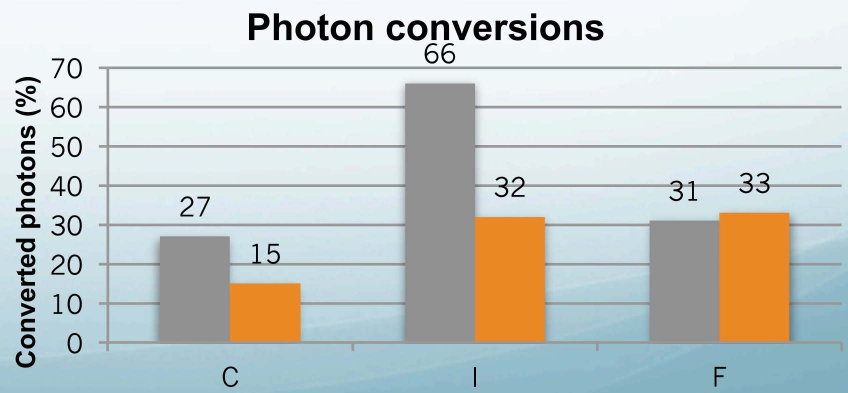
C	0 – 0.8
I	0.8 – 1.6
F	1.6 – 2.4

■ CMS
■ Upgrade

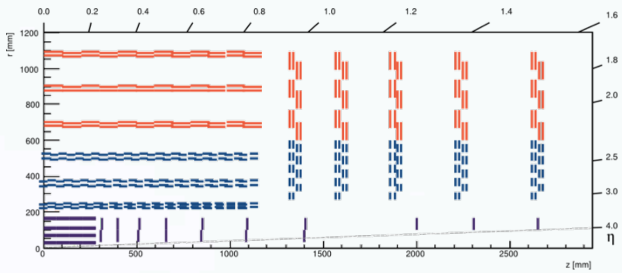




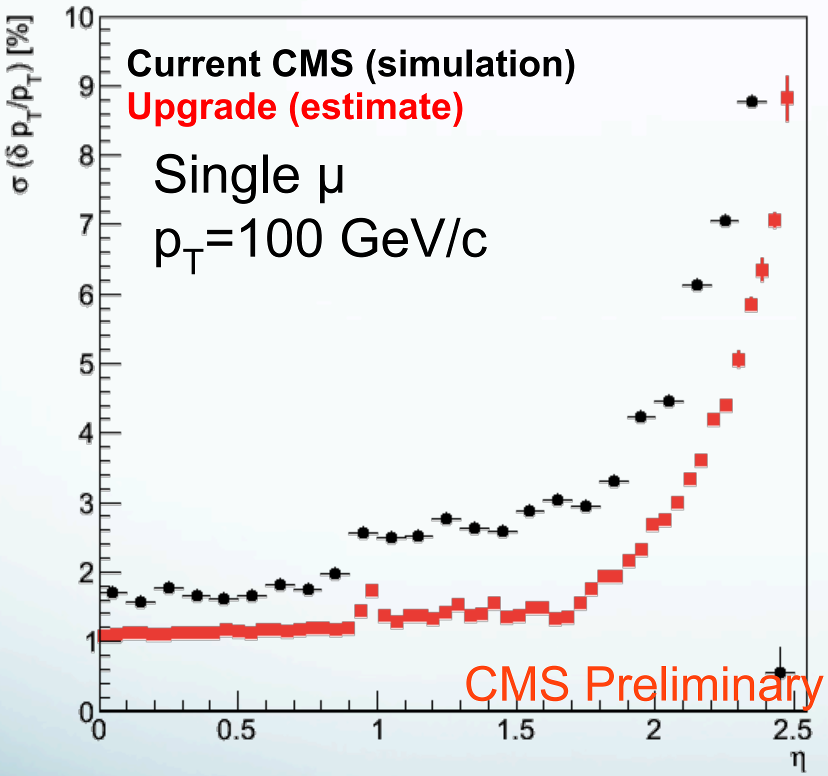


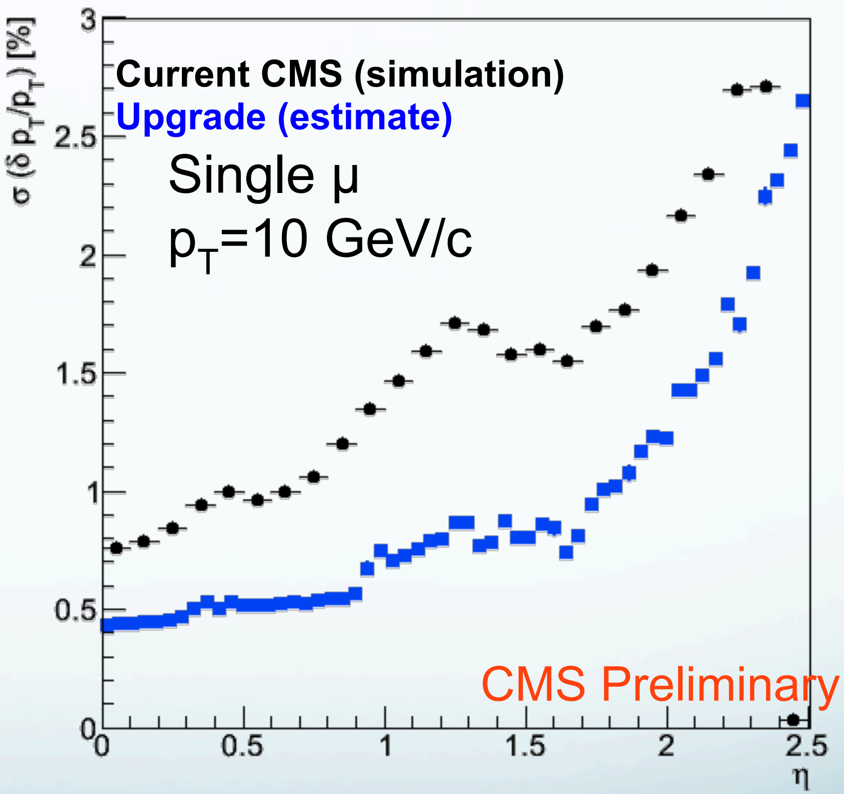


Tracking resolution



p_T resolution of single muons



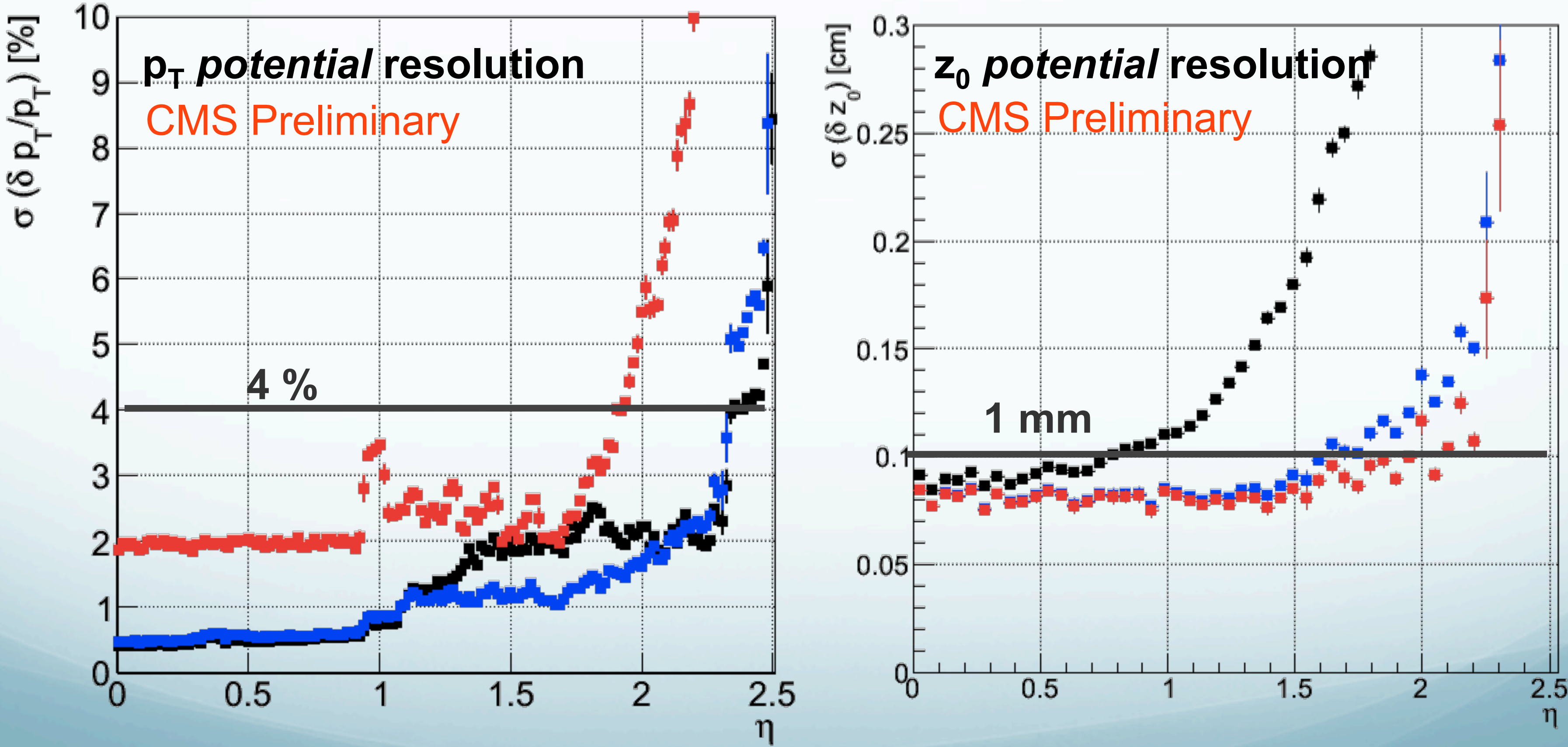


Significant improvement expected in the whole p_T range

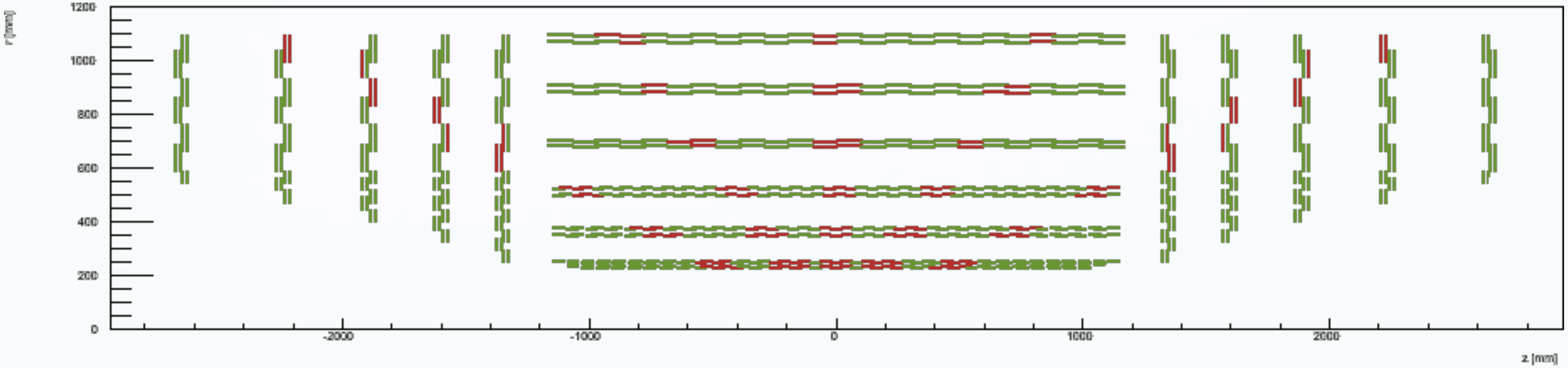
Tracking resolution @ Level-1

Single μ p_T=2 GeV/c
Single μ p_T=10 GeV/c
Single μ p_T=100 GeV/c

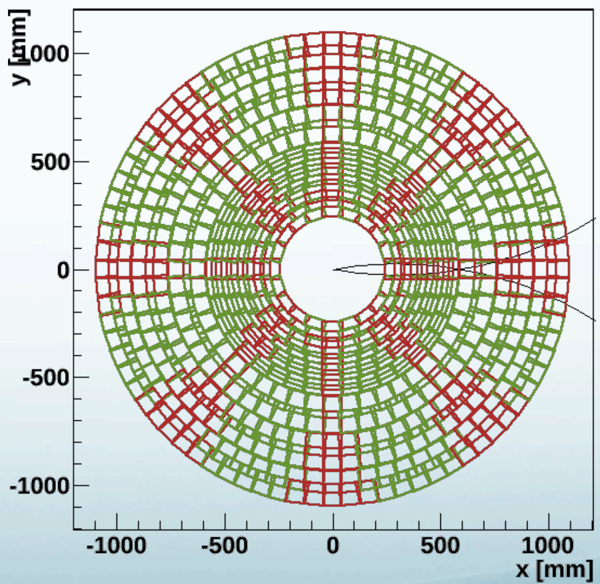
Potential p_T resolution using all stub info



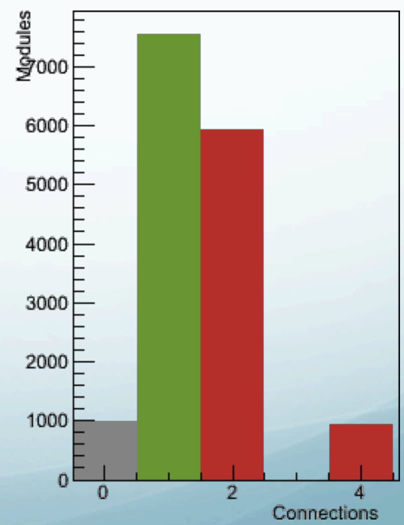
Track finding @ Level-1



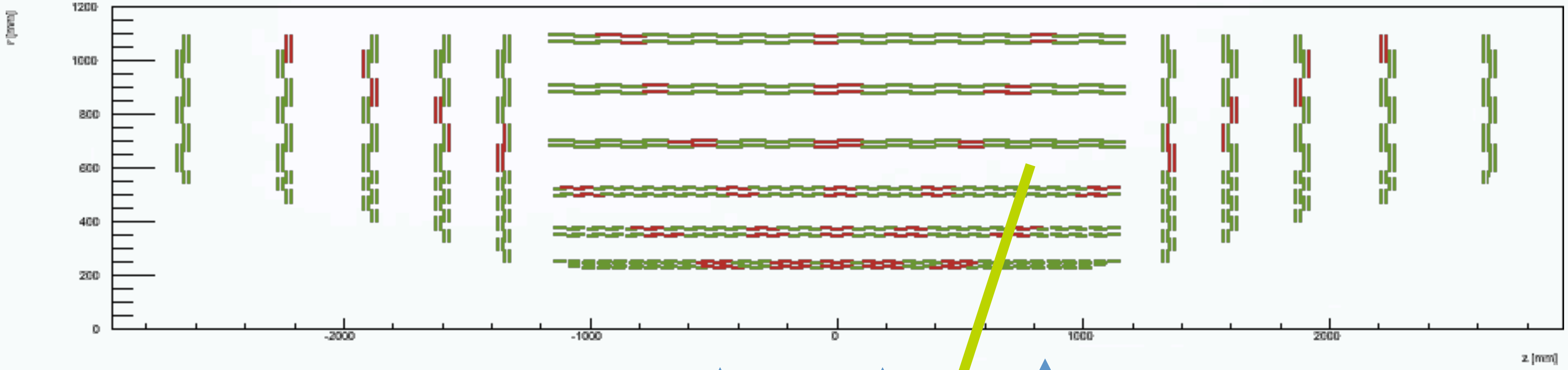
- Each sector independent
- Overlap regions depend on
  - Luminous region Δz
  - Minimum p_T cut



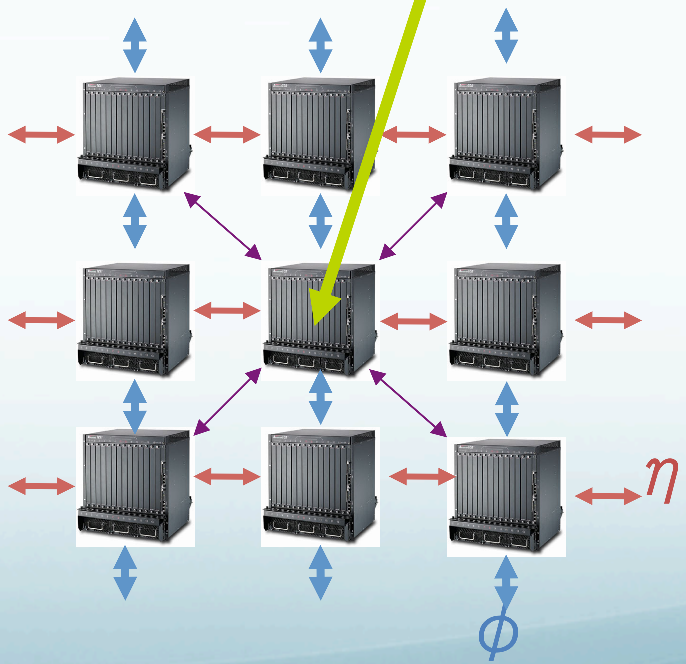
Number of sectors connected to a module



Track finding @ Level-1



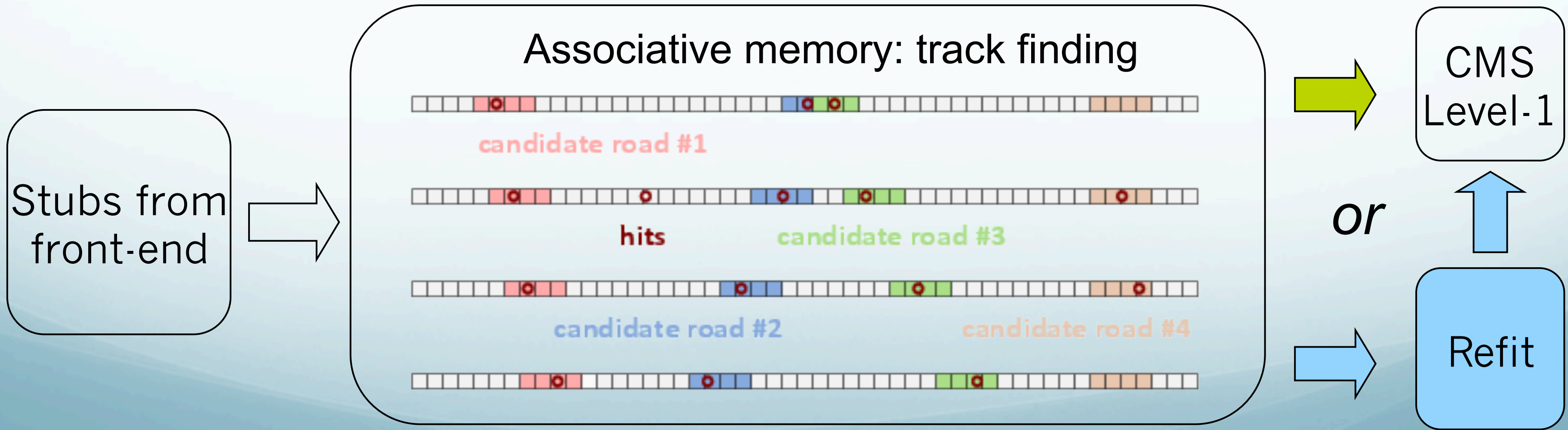
Simple
Trigger Tower
Interconnections



Each box represents
a trigger tower

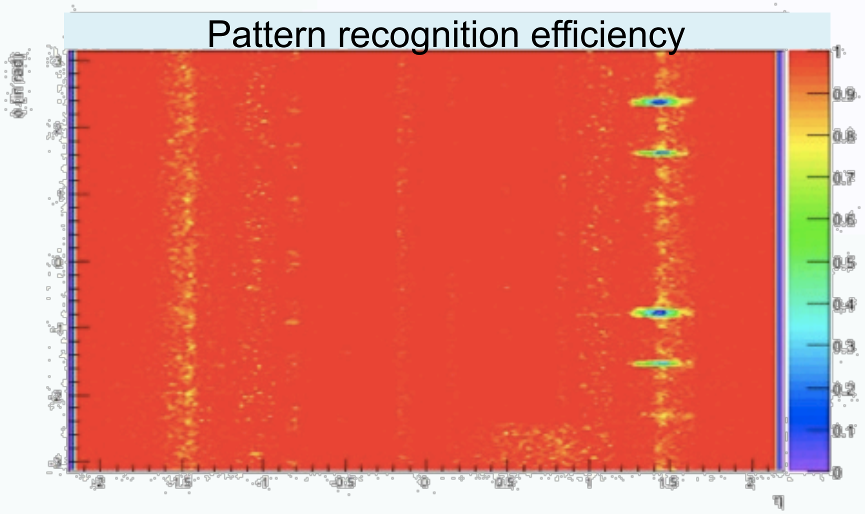
Track finding at Level-1

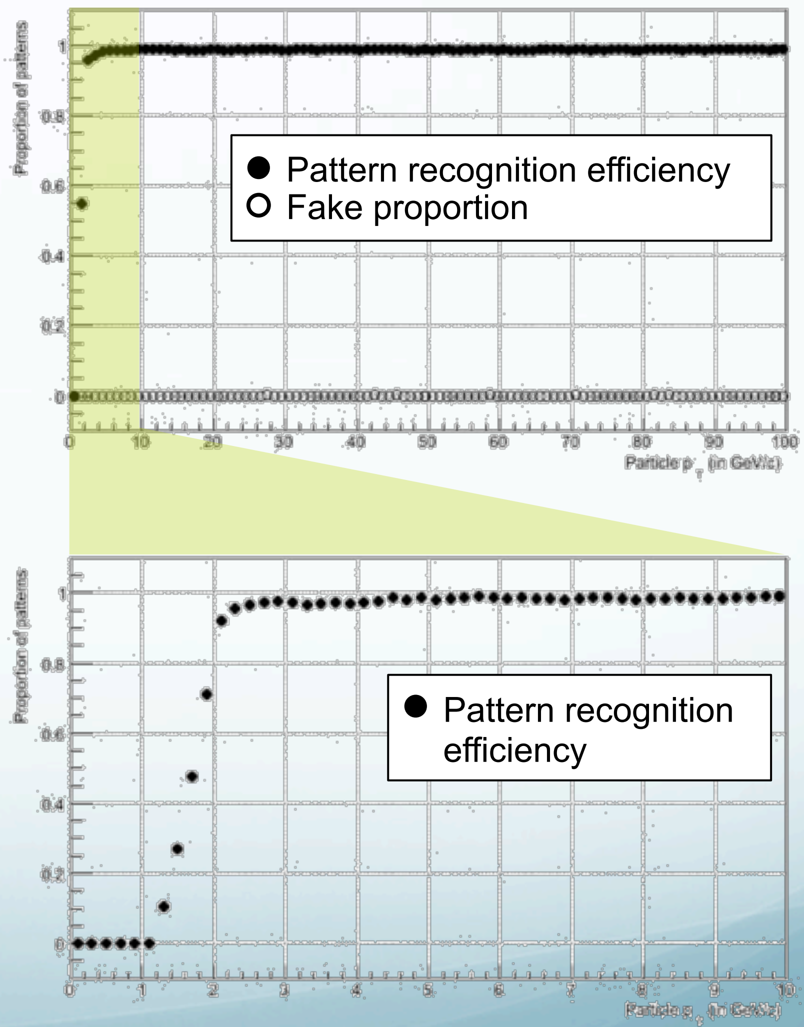
- Within a latency of O(μs): Associative Memories
  - Pattern matching using AM technologies dates back to CDF SVT to enhance collection of events with long-lived hadrons
  - HL-LHC: much higher occupancy, higher event rates, higher granularity
  - Plan of development
    - ★ **Software emulation** (ongoing)
    - ★ Build a **demonstrator system** using ATLAS **F**ast**T**rac**K**er boards (started)
    - ★ Develop dedicated AM chips and boards



Trigger board emulation

VERY preliminary results!





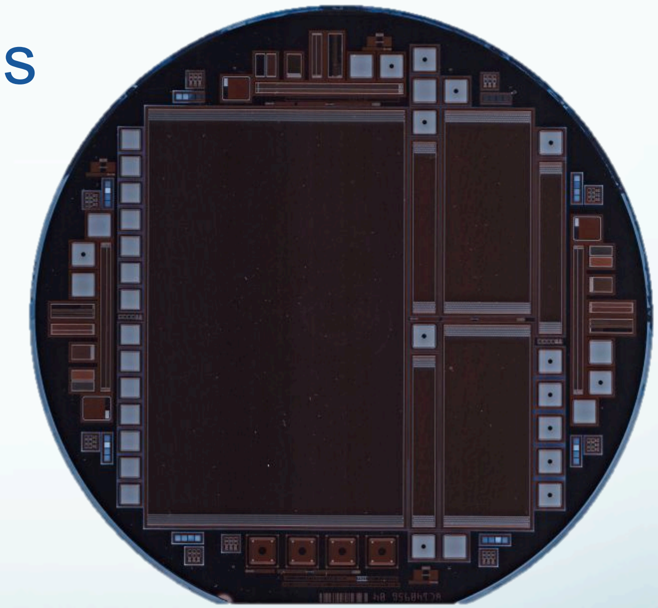
- Preliminary studies indicate that full efficiency can be achieved over the whole η range
- Sharp turn-on curve of the efficiency around ~1.5 GeV/c
- Implementation in hardware?

Sensors R&D

- Key element to achieve enhanced radiation tolerance and improved performance

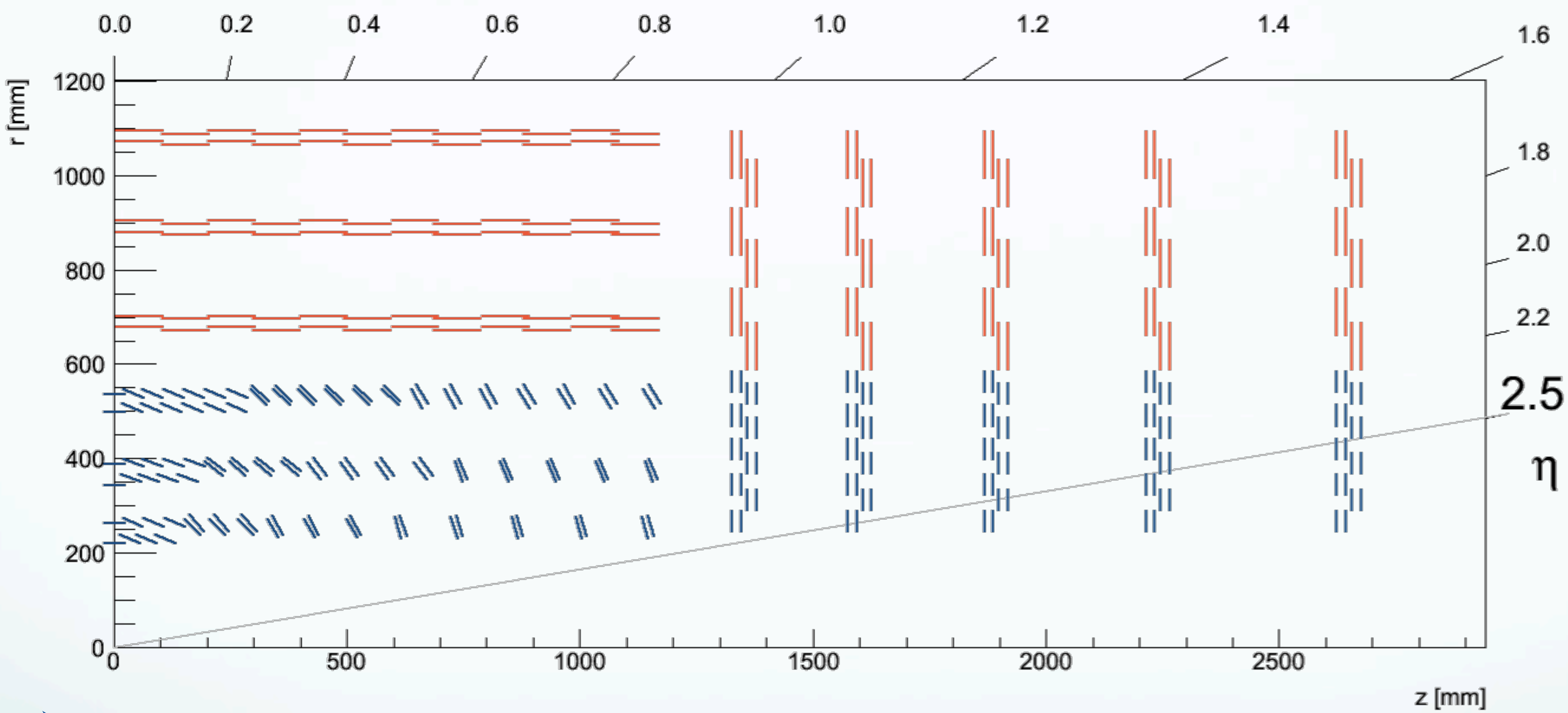
- Select material and technology that offers adequate performance after irradiation

- Understand in detail sensors properties
  - Signal
    - Design of readout electronics
  - Leakage current vs operating temperature
    - Module design
    - Cooling requirements
    - Sealing
  - “Annealing”
    - Requirements for maintenance periods



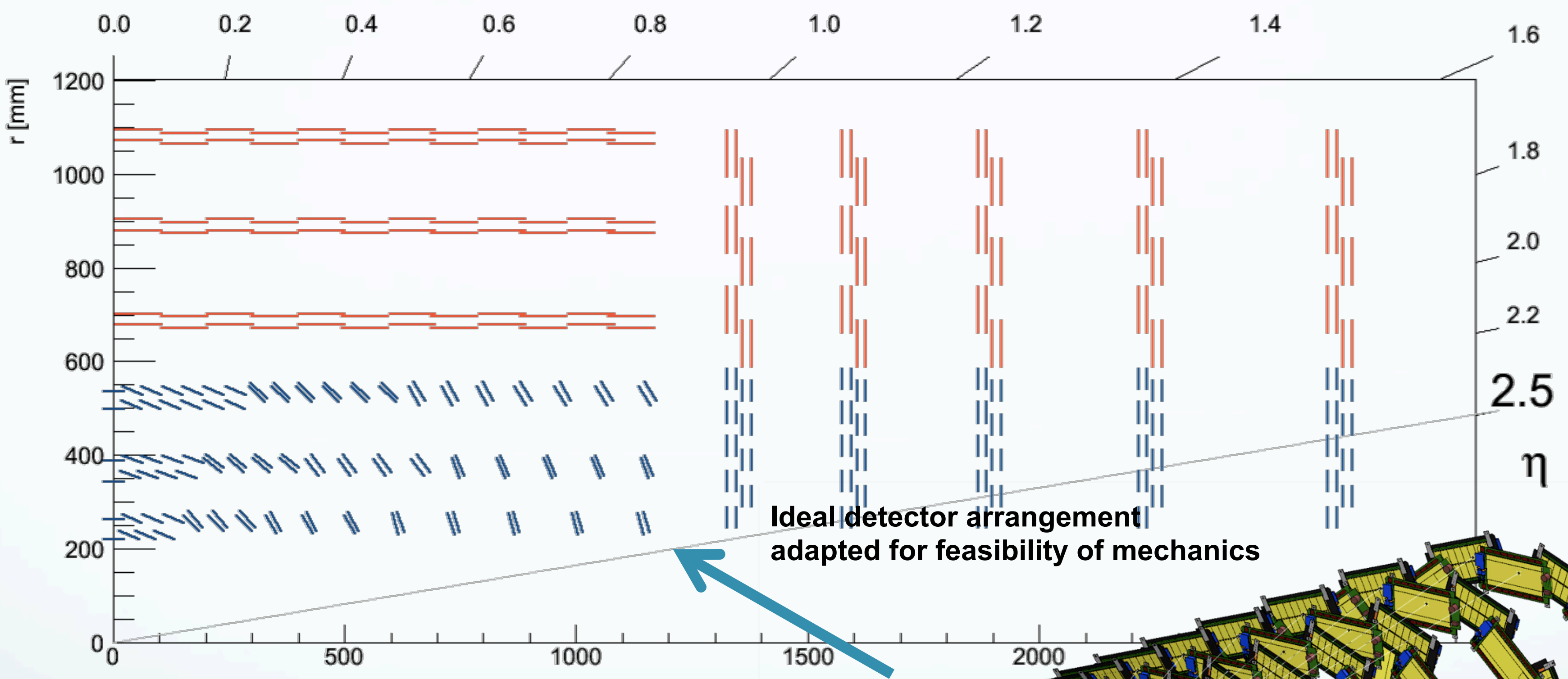
- Identify and qualify vendors who can provide sensors of the appropriate quality

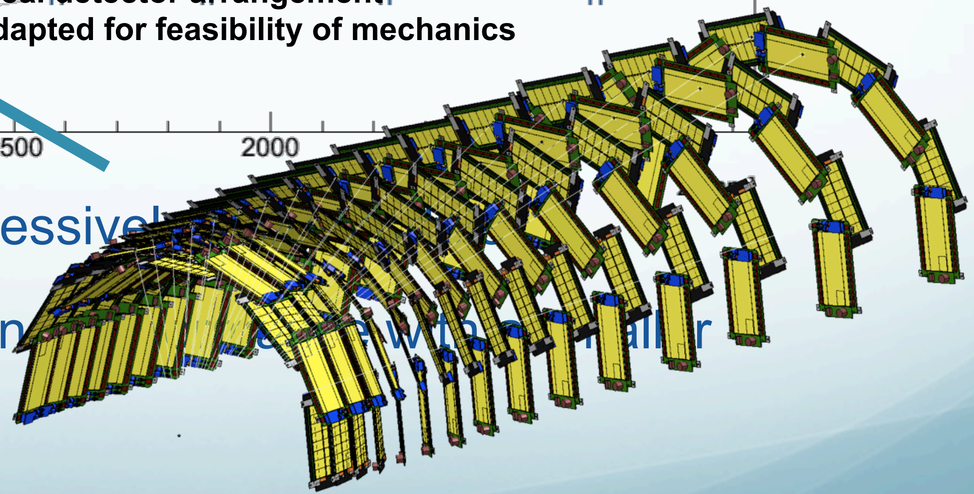
Beyond baseline?



- Variant of Inner Barrel with progressively tilted modules
- Same coverage and same tracking performance with a smaller number of modules
- Is it worth the effort?

Beyond baseline?

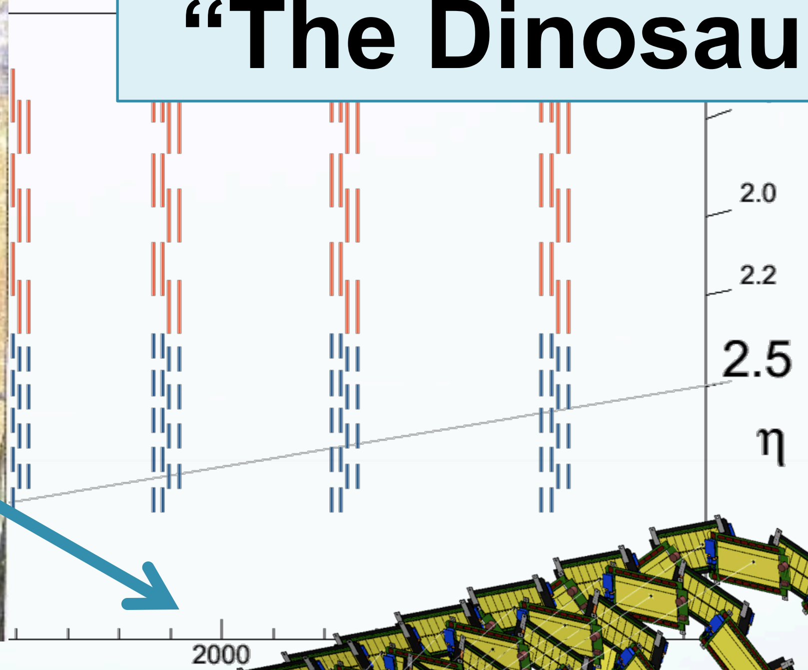


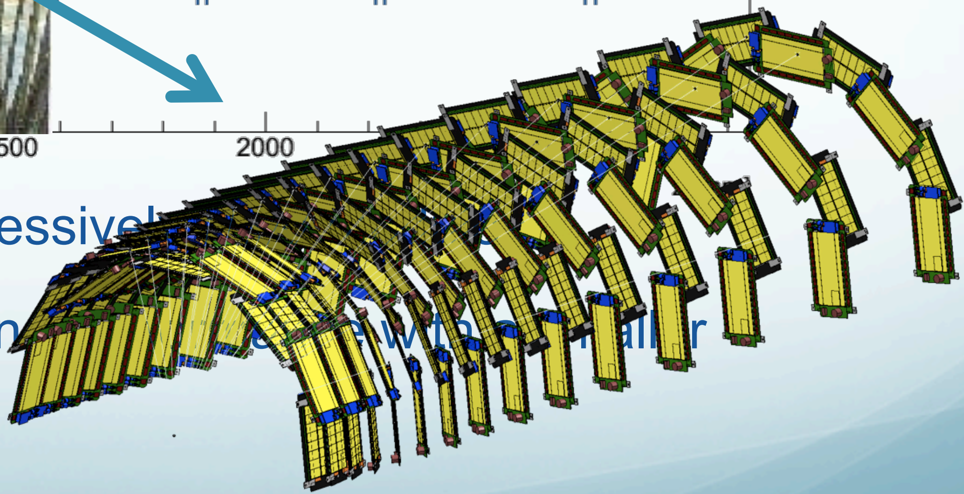


- Variant of Inner Barrel with progressive
- Same coverage and same trackin
  number of modules
- Is it worth the effort?

Also Known As:

"The Dinosaur"

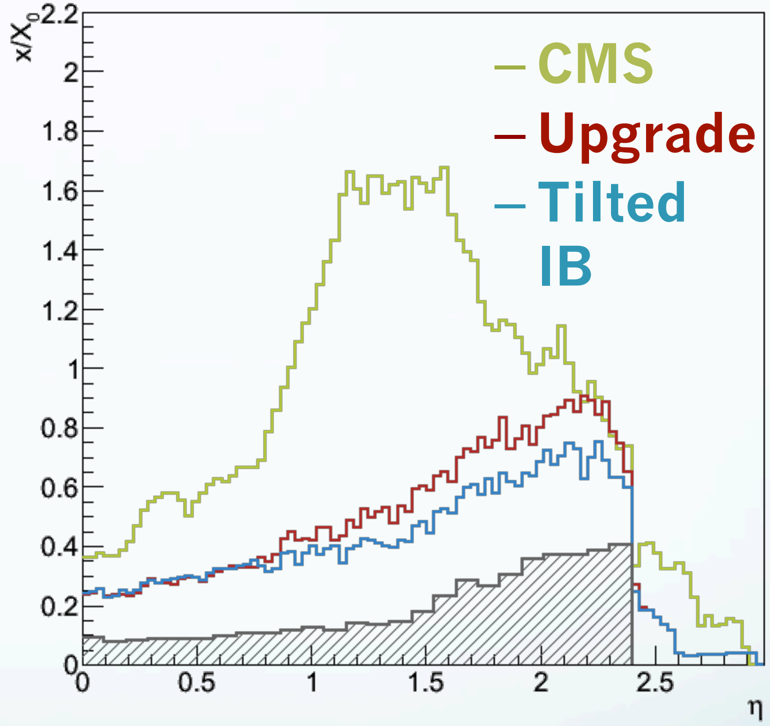




- Variant of Inner Barrel with progressivel
- Same coverage and same trackin ... all r number of modules
- Is it worth the effort?

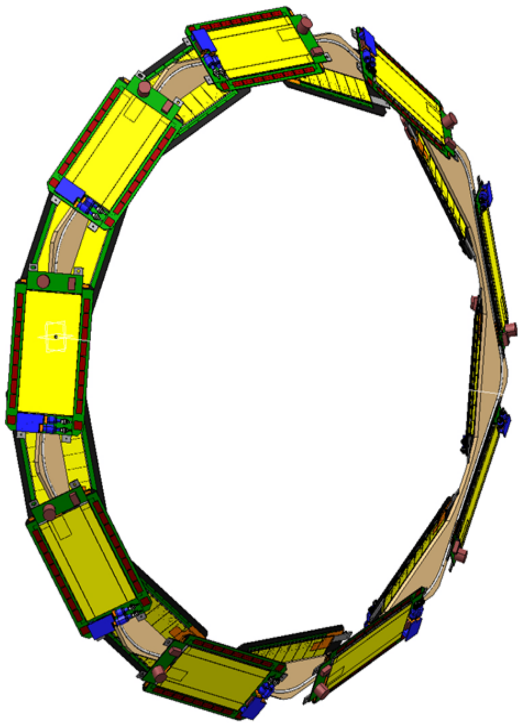
Advantages

- Smaller N of modules
  - N of PS modules 4164→ 2836 (−30%)
    - ★ For the inner barrel only
- Smaller power
  - 23 kW → 16 kW
  - Nicely matching TOB and each TEC!
- Interesting reduction in material
  - In a volume far from the calorimeters

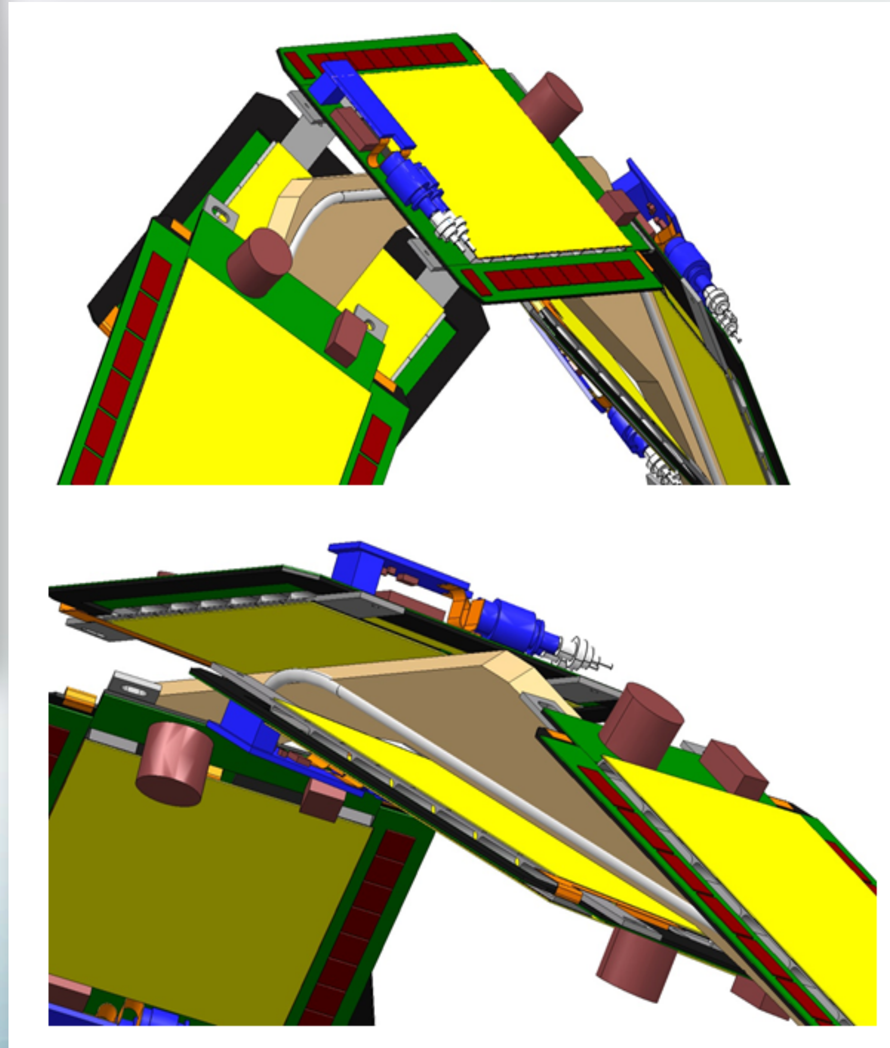


- And finally also some relevant financial saving
  - … ~ 5% on the overall Tracker cost!

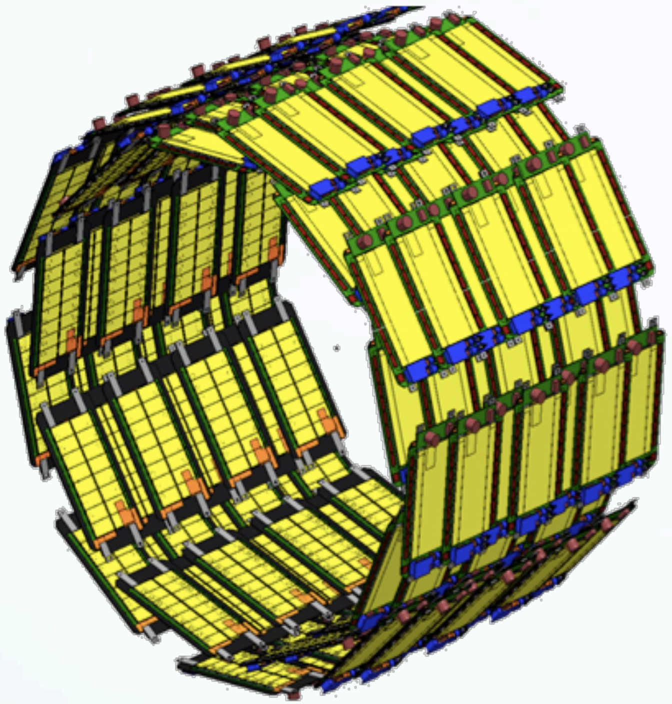
3D geometry studies



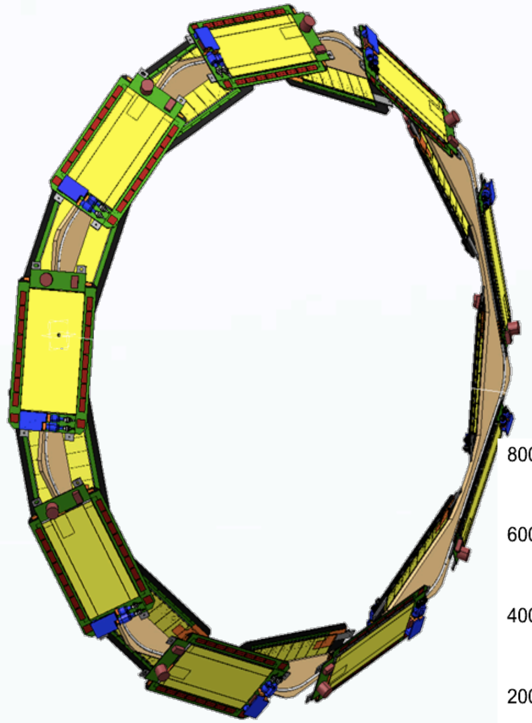
Single ring support



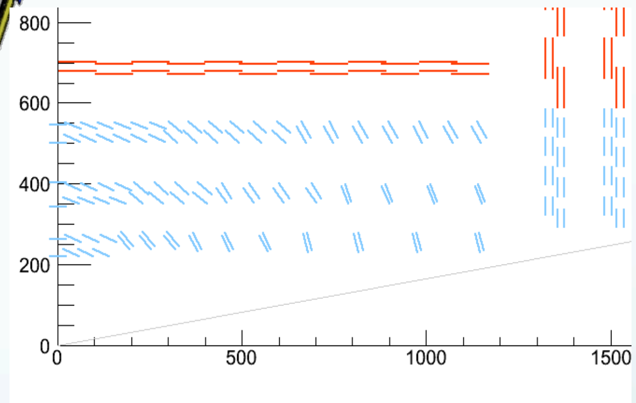
3D geometry studies



Central region
with horizontal modules



End Rings
with Tilted modules

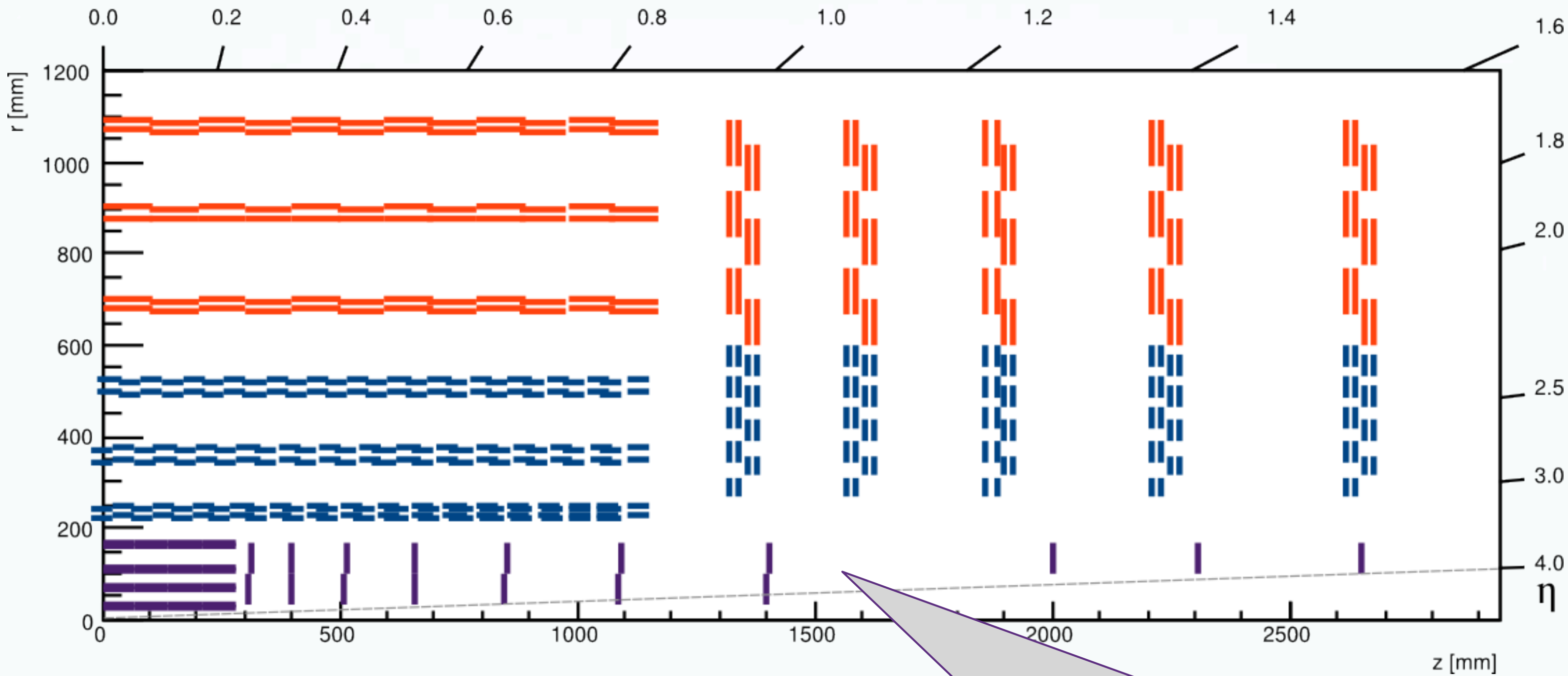


- Use the tilted modules where they are the most valuable to gain material, in the forward region
- In the central region the modules are arranged horizontally

Phase-2 pixel

- The phase-1 pixel detector is not the CMS ultimate pixel
- Construction time is shorter, ~ 2 more years to converge on a design compared to the outer tracker
- Discussions started; convergence on some basic concepts
  - Aiming at a significantly smaller pixel size. Possibly as small as 30×100 μm^2?
  - 65 nm seems to be a good technology choice
    - Strong technology node, likely to be available for very long
    - Can squeeze 4× digital logic in same area wrt 130 nm
  - Thin planar sensors with small pixels could be a robust baseline
  - 3d silicon very appealing option with potentially excellent performance
    - Need to evaluate production issues and cost
  - Several important system issues need to be addressed
    - Optical components and DC-DC converter electronics unlikely to be useable in the pixel volume!

Phase-2 pixel



Fluence 2×10^{16} neq cm^{-2} @ r=5 cm

With current CMS pixel @600V
CCE = 50% at 10^{16} neq cm^{-2}

- **Tracking up to η≈4**
- One more open question about trigger
  - Data reduction not applicable below ~20 cm
  - Maybe Region-Of-Interest @Level-1.5? (with input from calorimeters/muons?)

Summary and outlook

- Designing an Outer Tracker with:
  - Higher granularity
  - Enhanced radiation hardness
  - Improved tracking performance (… and lighter!)
  - L1 Track finding capability
    - Reconstruct tracks above ~ 2 GeV
    - With ~ 1mm z_0 resolution
- All the necessary R&D activities are ongoing
  - A lot of interesting and creative work!
- Draft schedule developed for delivery in LS3
- Phase 2 pixel project on the starting blocks
  - Many open questions to be answered!